



**US Army Corps  
of Engineers®**  
Engineer Research and  
Development Center

## **Geophysical Surveys for Assessing Levee Foundation Conditions, Sacramento River Levees, Sacramento, CA**

José L. Llopis, Eric W. Smith, and Ryan E. North

July 2007



# **Geophysical Surveys for Assessing Levee Foundation Conditions, Sacramento River Levees, Sacramento, CA**

José L. Llopis, Eric W. Smith, and Ryan E. North

*Geotechnical and Structures Laboratory*  
*U.S. Army Engineer Research and Development Center*  
*3909 Halls Ferry Road*  
*Vicksburg, MS 39180-6199*

Final report

Approved for public release; distribution is unlimited.

Prepared for Headquarters, U.S. Army Corps of Engineers  
Washington, DC 20314-1000

**Abstract:** Effective flood and coastal storm emergency response depends on the ability of emergency managers to obtain information on the condition of flood damage reduction structures in near-real time. This report describes the results of a series of geophysical investigations performed to determine the potential of geophysical methods to provide supplemental geologic data between existing borings in a rapid fashion in an area of complex geology located along the toe of the Sacramento River levees. The geophysical study was conducted along selected portions of the Sacramento River levee between Natomas Cross Canal and Powerline Road. Electromagnetic, ground penetrating radar and capacitively-coupled resistivity surveys were conducted to infer soil type.

**DISCLAIMER:** The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

**DESTROY THIS REPORT WHEN NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.**

# Contents

<b>Figures and Table.....</b>	<b>iv</b>
<b>Preface.....</b>	<b>v</b>
<b>Unit Conversion Factors.....</b>	<b>vi</b>
<b>1 Introduction.....</b>	<b>1</b>
Background .....	1
Purpose and scope .....	3
Study area.....	3
Geologic setting.....	3
<b>2 Geophysical Test Principles and Field Procedures.....</b>	<b>10</b>
Electromagnetic surveys .....	10
Capacitively-coupled resistivity.....	13
Ground penetrating radar (GPR) surveys .....	15
<b>3 Geophysical Test Results and Interpretation .....</b>	<b>19</b>
Site 1 .....	19
<i>Electrical conductivity surveys.....</i>	19
<i>GPR surveys.....</i>	22
Site 2 .....	23
<i>Electrical conductivity surveys.....</i>	23
<i>GPR surveys.....</i>	24
Site 3 .....	25
<b>4 Summary, Conclusions, and Recommendations.....</b>	<b>30</b>
Summary and conclusions .....	30
Recommendations .....	31
<b>References.....</b>	<b>33</b>
<b>Appendix A: Soil Profiles, Site 1.....</b>	<b>34</b>
<b>Appendix B: GPR Records, 100 MHz, Site 1.....</b>	<b>39</b>
<b>Appendix C: GPR Records, 50 MHz, Site 1 .....</b>	<b>43</b>
<b>Appendix D: Soil Profiles, Site 2.....</b>	<b>47</b>
<b>Appendix E: GPR Records, 100 MHz, Site 2 .....</b>	<b>53</b>
<b>Appendix F: Soil Profiles, Site 3 .....</b>	<b>57</b>
<b>Report Documentation Page</b>	



# Figures and Table

## Figures

Figure 1. Site map showing the locations of the three test sites located on the east bank of the Sacramento River. ....	4
Figure 2. Geomorphology map, east levee, Sacramento River between Natomas Cross Canal and Powerline Road (from URS 2002). ....	7
Figure 3. Geonics Ltd. EM31 conductivity meter being used during a typical survey. ....	12
Figure 4. Geonics Ltd. EM34 conductivity meter being used during a typical survey. ....	13
Figure 5. Illustration of the Geometrics OhmMapper capacitively-coupled resistivity system being hand-towed.....	14
Figure 6. Illustration of GPR (a.) being towed over different shaped objects and interface and (b.) resulting GPR trace. ....	15
Figure 7. Sensors and Software pE 100 GPR system with 100-MHz antennas. ....	17
Figure 8. Cart-mounted pE 100 control unit and DVL. ....	18
Figure 9. Plan view of survey line, Site 1.....	20
Figure 10. Metal fence located adjacent to survey line, Site 1.....	21
Figure 11. Barn with metal roof adjacent to survey line, Site 1.....	21
Figure 12. Electrical conductivity surveys, Site 1, landside toe. ....	22
Figure 13. Geophysical survey line layout, Site 2.....	24
Figure 14. A portion of the geophysical survey line, Site 2.....	25
Figure 15. Electrical conductivity surveys, Site 1, landside toe. ....	26
Figure 16. Geophysical survey line layout, Site 3. ....	27
Figure 17. Steel pipe fence adjacent to survey line between approximate UTM northings 4280480 and 4280380, Site 3.....	28
Figure 18. Private residence adjacent to survey line, approximate UTM northing 4280250, Site 3.....	28
Figure 19. Electrical conductivity surveys, Site 3, landside toe. ....	29

## Table

Table 1. Electrical resistivity values of some common rocks and minerals. ....	11
--	----

## Preface

This report describes a research study funded by the U.S. Army Corps of Engineers (USACE) Technologies and Operational Innovations for Urban Watershed Networks (TOWNS) Research Program (now the Emergency Management Technologies focus area of the Flood and Coastal Storm Damage Reduction Research Program) and conducted by the U.S. Army Engineer Research and Development Center (ERDC). The purpose of this report was to determine the feasibility of using surface-based geophysical surveys to rapidly map and characterize the soils and geologic conditions along the toe of a levee. The field investigation was performed during the period 14–24 July 2004 along selected portions of the Sacramento River east (left) bank levee approximately 7 to 15 miles north-northwest of Sacramento, CA. The geophysical surveys included electromagnetic induction, ground penetrating radar, and capacitively-coupled resistivity. These measurements are used to infer soil-property information between existing borings along the toe of the levee.

The research described herein was conducted by José L. Llopis, Eric W. Smith, and Ryan E. North, Geotechnical and Structures Laboratory (GSL), ERDC, Vicksburg, MS. This publication was prepared by Llopis, under the general supervision of Dr. Lillian D. Wakeley, Chief, Engineering Geology and Geophysics Branch; Dr. Robert L. Hall, Chief, Geosciences and Structures Division; Dr. William P. Grogan, Deputy Director; and Dr. David W. Pittman, Director, GSL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

## Unit Conversion Factors

Multiply	By	To Obtain
feet	0.304800	meters
miles	1.609	kilometers

# 1 Introduction

## Background

Since levees are a fundamental part of many flood damage reduction projects that protect life and property, their condition and performance in emergency flooding situations is of utmost importance. The U.S. Army Corps of Engineers (USACE) has conducted research and development activities related to levees in a number of research programs, including the Innovative Flood Program and its successor, the Technologies and Operational Innovations for Urban Watershed Networks (TOWNS) Research Program. Currently, research related to levee condition evaluation and assessment is being conducted under the auspices of the Emergency Management Technologies focus area of the Flood and Coastal Storm Damage Reduction Research Program. Developing the capability to rapidly obtain information about levee conditions and convey the data to decision makers during emergency operations, particularly in cases where levee failure is possible, is a primary objective of this research.

Levee failures are governed in large part by the soils that form the embankments and their foundations. Failure of a levee occurs as a result of the river scouring the toe of the levee, resulting in failure of the embankment into the channel, by overtopping of the embankment, and by seepage and piping. Water seepage through the levee embankment (through-seepage) can produce internal erosion of the levee soils. Foundation problems in levees usually are caused by under-seepage and are related to geologic conditions at the site.

Through-seepage is not normally a major concern for levees constructed of clay soils unless flood stage is long enough that the embankment becomes saturated, or when defects in the levee, such as animal burrows or desiccation cracks, produce concentrated flows. Seepage through levees constructed of silt and sand can produce erosion at the landside slope and lead to breaching of the levee if the seepage remains uncontrolled.

For a levee constructed on a highly erodible foundation of silt, sand, or local gravel deposits, seepage of water beneath the levee is more critical than through-seepage. Identifying erodible foundation soils is an important step in preventing levee failures. Because floodplain deposits underlie

levees, knowledge of the geology of local floodplain deposits is an important consideration in flood control management. Levee systems are often built atop highly permeable, relatively coarse-grained river deposits. These sediments represent old channels and courses of the river system abandoned during its history of meandering over the floodplain. These coarse-grained deposits represent the most likely locations for under-seepage in levee systems.

It is imperative that geologic features be identified in the earliest stages of a levee condition assessment so that other exploratory methods could be used to confirm their existence and map their distribution. Knowledge of fluvial processes and the ability to recognize depositional environments in the geologic record are the key to identifying locations along modern levees where under-seepage is most likely to occur. To gain more information about the foundation materials, borings are usually placed at predetermined distances, sometimes hundreds of meters apart, along the levee axis. Through the performance of Standard Penetration Testing (SPT) during the drilling of borings along with laboratory testing of soil samples, borings provide engineering soil properties as a function of depth at a given boring location. However, information about soils between borings must be interpolated. In some geologic conditions, where there are gradual or rather predictable soil changes, the interpolations may be adequate. In areas where the geology is more complex, interpolating the soil properties or conditions between borings may be inadequate or misleading. In the case of a geologically complex site, many more closely spaced borings would have to be placed to better define the subsurface conditions and can be more cost-effective than drilling closely spaced borings.

As an alternative to drilling additional very closely spaced borings, surface geophysical testing can be conducted between the more widely spaced borings to provide geologic information. In 2003 personnel of the U.S. Army Engineer Research and Development Center (ERDC) conducted a proof of principle study along U.S. International Boundary and Water Commission levees in the Lower Rio Grande Valley of Texas (Dunbar et al. 2003). The study consisted of conducting helicopter-borne electromagnetic surveys along the levees to obtain an overall assessment of soil conditions of the levees and their foundation materials. Anomalous areas were identified and investigated in greater detail using ground-based geophysical surveys, a cone penetrometer equipped with an electrical resistivity probe, and soil sampling. The study concluded that the combination of airborne and

ground-based geophysical surveys is an economical and reliable method for assessing levee conditions.

## **Purpose and scope**

Potential failure of levees in the Sacramento-San Joaquin delta of California has been identified as a critical engineering problem (e.g., Reid 2005, Hess and Sills 2004). Levees along the Sacramento River have experienced under-seepage during high water events (URS 2002). Because of the complex geology in this area it is difficult to predict where under-seepage is likely to occur, and thus where preventative or emergency measures should be prioritized. The purpose of this study was to determine the potential of geophysical methods to provide supplemental geologic data between existing borings in a rapid fashion—as would be desired for emergency situations—and for more complex geology than where the concept was tested. This report describes the results of a geophysical study conducted along selected portions of the Sacramento River levee between Natomas Cross Canal and Powerline Road. The study was funded by the TOWNS Research Program.

## **Study area**

The study was conducted along three selected reaches on the Sacramento River east (left) bank levee, approximately 7 to 15 miles north-northwest of Sacramento, CA. Stationing along the levee is expressed in this report by Reclamation District (RD) 1000 Levee Miles (LM), which is measured from LM 0.0 at Natomas Cross Canal and increase to the south (down-river). The three sites are located along a stretch of levee situated roughly between Sankey Road, immediately south of the Natomas Cross Canal (LM0.1), to approximate LM11, about 1.2 miles upriver from Powerline Road (Figure 1).

## **Geologic setting**

The following geologic information is excerpted from a 2002 report to the U.S. Army Engineer District, Sacramento (URS 2002):

The Sacramento Valley is underlain by a north-south trending asymmetrical syncline. It is bounded on the north by the Klamath Mountains, on the east by the



Figure 1. Site map showing the locations of the three test sites located on the east bank of the Sacramento River.

Sierra Nevada, on the west by the northern Coast Ranges, and on the south by the Stockton Arch. The synclinal structure involves Cretaceous (65- to 145-million-year-old) marine sedimentary rocks and Tertiary (2- to 65-million-year-old) marine and non-marine sedimentary rocks. These strata underlie alluvial fans, channel deposits, and floodplain deposits of Sacramento River and its tributaries.

The Sacramento River is a meandering drainage that flows generally from north to south. Along with its tributaries, the Sacramento River drains the northern Coast Ranges, Klamath Mountains, and the Northern Sierra Nevada. Since the late-1910s, the Sacramento River has been confined within man-made levees in the Natomas area. A system of bypasses accommodates overflows when the river when it is in flood stage. All geologic units exposed in the RD-1000 area are alluvial. These units are described below in order of oldest to youngest.

The Riverbank Formation, designated as Qrl in Figure 2, is the oldest geologic unit exposed in RD-1000 and immediate vicinity. It is estimated to be 130,000 to 450,000 years old (Marchand and Allwardt 1981). In the RD-1000 area, it is partially covered by younger alluvium and probably represents the distal (farthest from the source) edge of the formation. It consists of gravel, sand, and silt.

The Modesto Formation (designated as Qml in Figure 2) is exposed in alluvial terraces in the vicinity of the Sacramento River. The lower member of the Modesto Formation is exposed in RD-1000 and is approximately 29,000 to 42,000 years old (Marchand and Allwardt 1981). The Modesto Formation consists of gravel, sand, silt, and clay. These terraces are remnants of alluvial fans. Soils formed in the Modesto Formation have a distinct red color.

Basin deposits, designated as Qb, are fine-grained sediments deposited over floodplains. These floodplain deposits consist primarily of silt and clay and have a relatively low permeability due to their grain size.

Holocene (less than 10,000-year-old) alluvial deposits (Qa) consist of sand, silt, clay, and gravel derived from the Coast Ranges, Sierra Nevada, and Klamath



Mountains. These deposits are differentiated from stream channel deposits (Qsc), which occur along current drainages. The alluvial deposits (Qa) include natural levee deposits and former point bars, which are rich in granular material and have a relatively high permeability.

Over the past two million years, the Sacramento River has developed into a meandering drainage that changed its course as it drained the Sacramento Basin. As a meandering river develops, it deposits and erodes different parts of its banks and channel. The hydraulic flow is fastest at the outside of a meander where the river forms a cut bank and increases the curvature of its channel. At the same time, the slower moving current on the inside of the meander deposits its sediment load to form point bars. As meanders develop, the curvature becomes so extreme that the river eventually finds a path of least resistance by cutting off the meander. These cutoff meanders leave swampy backwaters known as oxbows that eventually silt up. A floodplain of a meandering stream typically contains silty and clayey deposits of former meanders or oxbows, and granular deposits of former point bars.

During flood stage, the river overflows its banks and deposits sediment over the floodplain or flood basin. The first sediments to be deposited during the flood stage are the coarser-grained sediments adjacent to the river channel. These coarser sediments pile up, forming natural levee deposits.

The result of the meandering river dynamics is as follows:

- deposition of relatively fine-grained sediments (silt and clay) in the active channel,

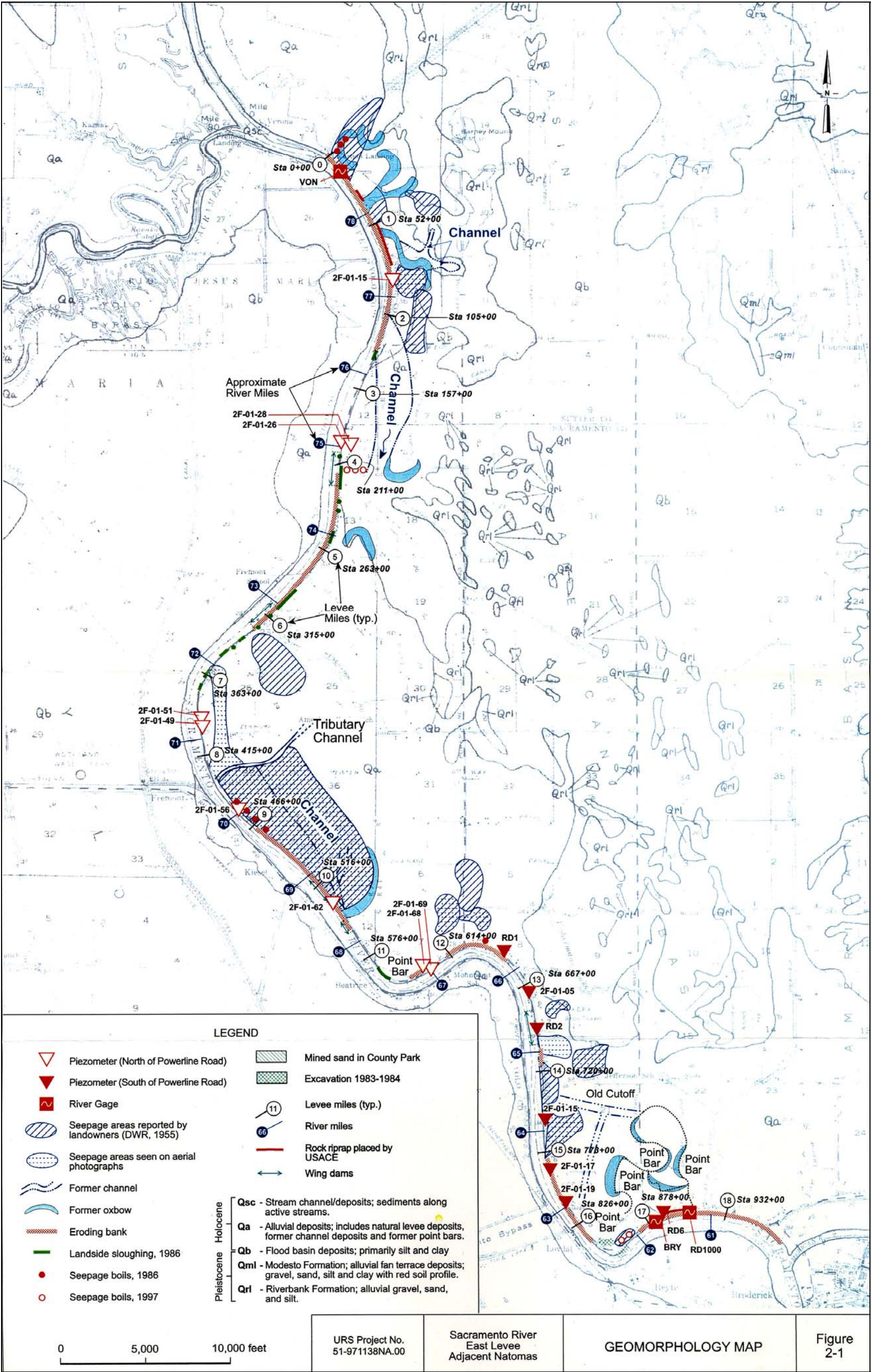


Figure 2. Geomorphology map, east levee, Sacramento River between Natomas Cross Canal and Powerline Road (from URS 2002).

- deposition of relatively coarse sediments (sand and gravel) in point bars and natural levee deposits; and
- deposition of relatively fine sediments on the floodplain (silt and clay).

The geomorphologic expressions of former channels, former natural levees, former oxbows, and former point bars show up as tonal variations associated with adjacent soils of differing grain size and permeability. This geomorphic evidence becomes hidden over time as floods deposit new soil over the old features and human activity obscures the natural landscape.



## **2 Geophysical Test Principles and Field Procedures**

This section describes the surface geophysical methods and field procedures used at each of the test sites. The geophysical methods used at the sites include electromagnetic (EM), capacitively-coupled electrical resistivity, and ground penetrating radar (GPR).

The geophysical tools are used to take measurements along survey lines adjacent to the levee toe. The measurements are interpreted to infer the geologic conditions beneath the survey line. Inferences regarding lateral and vertical soil changes may be made. Also, anomalous areas may be noted for further exploration. An anomaly is a departure from normal or background conditions.

Each geophysical method uses different physical principles to measure the properties of the subsurface. Therefore each survey method is affected differently by the subsurface conditions and consequently each survey line type may indicate different anomaly locations. When the surveys are completed several anomalies may be identified for each geophysical method. By using different geophysical methods, areas considered for future exploration can be prioritized based on the number of surveys that agree that a particular location is anomalous. For example, if three different survey methods indicate that a certain area is anomalous then that area is given a higher priority for future attention over an area that is identified as anomalous by only one survey method.

### **Electromagnetic surveys**

EM induction is used to measure the apparent electrical conductivity (inverse of electrical resistivity) of subsurface materials and to detect buried metallic items. Electrical conductivity is a measure of the degree to which the soil conducts an electrical current and can be used to infer geologic materials and the location of the water table. Conductivity values vary over several orders of magnitude depending on the type of earth material (Table 1). Major factors influencing the conductivity measurement are the amount of pore fluid present, the salinity of the pore fluid, the presence of conductive minerals, and the amount of fracturing.

Table 1 lists the conductivity values of common rocks and soil materials. Sedimentary rocks, because of their higher porosity and greater water content, have higher conductivity values than intact igneous and metamorphic rocks. Wet soils and groundwater have even higher conductivity values. Clayey soil normally has a higher conductivity than a sandy soil (Locke 2000a).

**Table 1. Electrical resistivity values of some common rocks and minerals.**

Material	Resistivity, $\Omega\cdot\text{m}$	Conductivity, milliSiemens/m (mS/m)
<b>Igneous and Metamorphic Rocks</b>		
Granite	5x10 <sup>3</sup> - 10 <sup>6</sup>	0.001 - 0.2
Basalt	10 <sup>3</sup> - 10 <sup>6</sup>	0.001 - 1
Slate	6x10 <sup>2</sup> - 4x10 <sup>7</sup>	2.5x10 <sup>-5</sup> - 1.7
Marble	10 <sup>2</sup> - 2.5x10 <sup>8</sup>	4x10 <sup>-6</sup> - 10
Quartzite	10 <sup>2</sup> - 2x10 <sup>8</sup>	5x10 <sup>-6</sup> - 10
<b>Sedimentary Rocks</b>		
Sandstone	8 - 4x10 <sup>3</sup>	0.25 - 125
Shale	20 - 2x10 <sup>3</sup>	0.5 - 50
Limestone	50 - 4x10 <sup>2</sup>	2.5 - 20
<b>Soils and Water</b>		
Clay	1 - 1000	1 - 1000
Alluvium	10 - 800	1.25 - 100
Groundwater (fresh)	10 - 100	10 - 100
Sea water	0.2	5000

Source: Keller and Frischknecht 1966.

The instrumentation used to measure soil conductivity consists of a transmitter (Tx) and receiver (Rx) coil separated by a certain distance. An alternating current is passed through the Tx coil, thus generating a primary time-varying magnetic field. This primary field induces eddy currents in subsurface conductive materials. The induced eddy currents are the source of a secondary magnetic field, which is detected by the Rx coil along with the primary field.

Two components of the induced magnetic field are measured by the EM system. The first is the quadrature phase, sometimes referred to as the out-of-phase or imaginary component. Apparent ground terrain conductivity is determined from the quadrature component. Disturbances in the subsurface caused by compaction, sediment-filled abandoned channels,

soil removal and fill activities, buried objects, or voids may produce conductivity readings different from background values, thus indicating anomalous areas. The inphase component is very sensitive to metallic objects and therefore is useful when looking for buried metal such as metal rails, rebar, or electrical wires.

Geonics Ltd. EM31 and EM34 meters were used in this investigation. The Tx and Rx coils for the EM31 are set at a fixed distance of 3 m. The EM31 has a depth of investigation of about 4.5 m. The field operator carries the EM31 across the site at normal walking speeds to acquire continuous data. The data can be collected along a single line or they can be collected continuously along several parallel lines. The line separation varies depending on the purpose of the survey and site conditions. The instrument can acquire data point by point (manual sampling), or it can send data to an external logger via an RS-232 data link, thus allowing the unit to be vehicular mounted and integrated into a GPS - (global positioning system) based survey system. A Trimble AG-132 GPS in conjunction with the Omnistar satellite differential positioning information service was used to obtain sub-meter positioning accuracy. The data can be plotted in profile form showing a profile line. If several survey lines of data have been collected at a site the data can be plotted showing a contour map of conductivity and in-phase values. The EM31 is shown in operation in Figure 3.

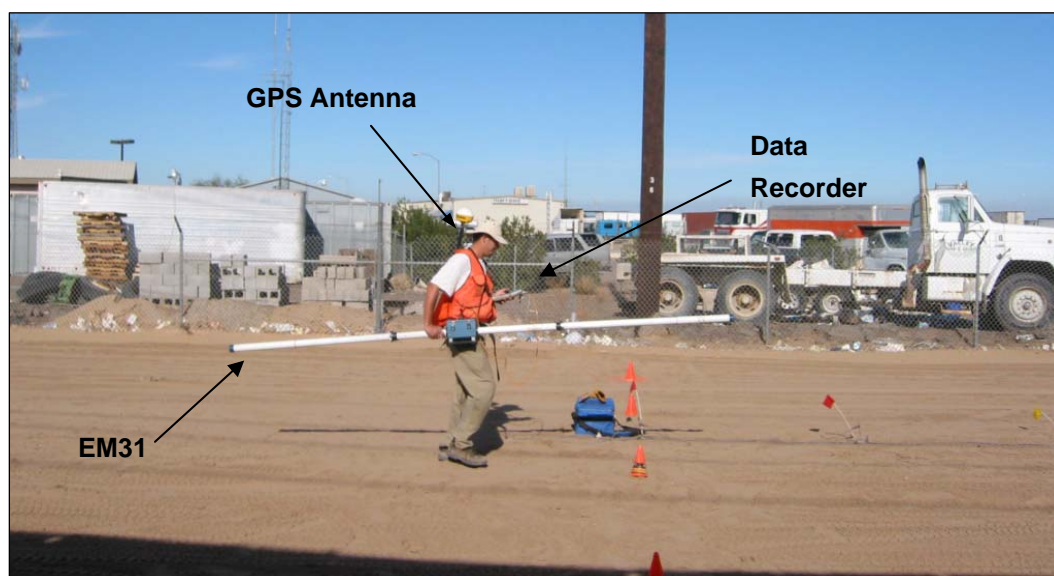


Figure 3. Geonics Ltd. EM31 conductivity meter being used during a typical survey.

Unlike the EM31 with a fixed coil separation, the EM34 can be operated at Tx-Rx coil separations of 10, 20, or 40 m. The greater the Tx-Rx coil

separation the greater is the depth of investigation. EM34 data can be collected in the vertical dipole mode (coils flat on the ground surface) or in the horizontal dipole mode (coils on edge and co-planar). The vertical dipole mode allows for a greater depth of investigation and is less sensitive to near-surface materials. For this investigation the vertical dipole mode and coil separations of 10 and 20 m were used resulting in depths of exploration of about 15 and 30 m, respectively. Data along the profile lines were collected at 10-m intervals with the exception of Site 1 where data were collected at 20-m intervals when using the 20-m intercoil configuration. Figure 4 shows the EM34 in operation.

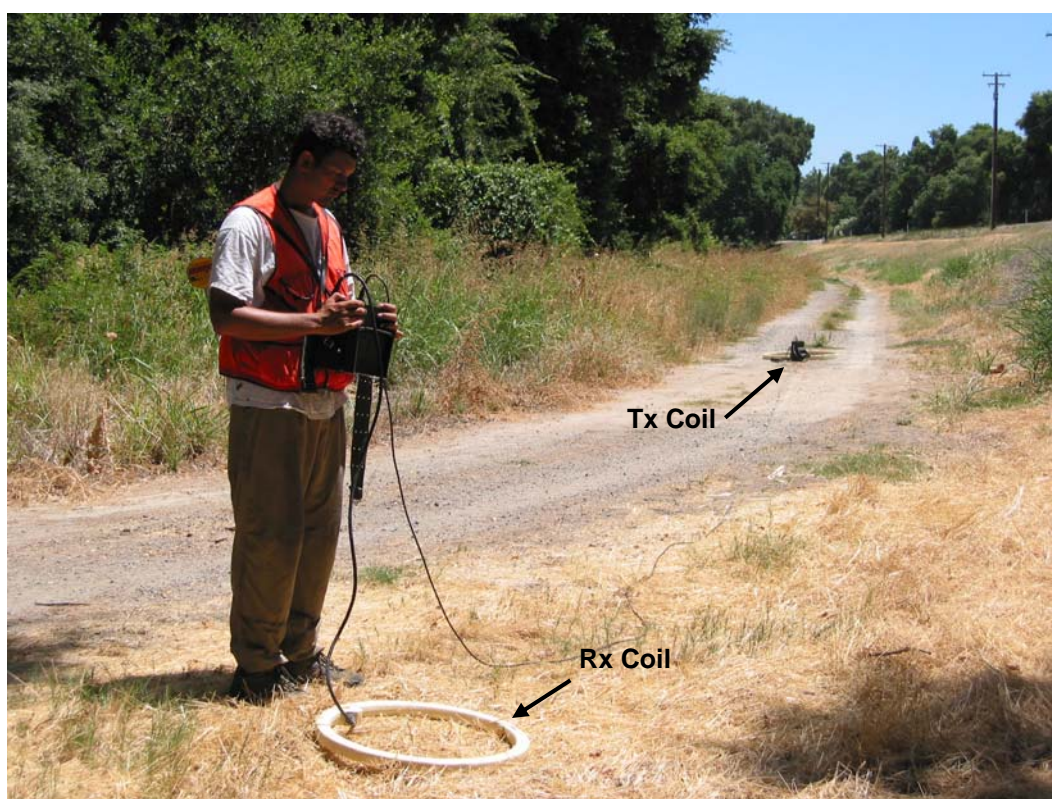


Figure 4. Geonics Ltd. EM34 conductivity meter being used during a typical survey.

### Capacitively-coupled resistivity

An instrument using the capacitively-coupled resistivity (CCR) principle of operation also was used in this investigation to collect soil conductivity information. The CCR principle of operation is similar to the direct current (DC) resistivity method. Instead of burying electrodes to inject current into the ground as is the case in DC resistivity surveying the current is “injected” capacitively into the ground. A transmitter electrifies two coaxial cables (transmitter dipole) with a 16.5 Hz alternating-current (AC)

signal. The dipole electrodes consist of coaxial cables in which the coaxial-cable shield acts as one plate of a capacitor and the earth as the other plate. A matched receiver, automatically tuned to the transmitter frequency, measures the associated voltage picked up on the receiver's dipole cables. The receiver then transmits a voltage measurement, normalized to current, to the logging console.

A Geometrics OhmMapper capacitively-coupled resistivity system was used to collect the resistivity data. The system used in this investigation uses one receiver allowing for one n-spacing to be collected per survey pass. Figure 5 is a diagram of the OhmMapper with the one receiver set-up. Multiple passes over the survey line using larger n-spacings are typically performed to provide lateral as well as depth information. Newer versions of the OhmMapper allow up to five receivers to be used per survey pass thus making the data collection procedure more efficient. The OhmMapper can be hand- or vehicle-towed (Figure 5). The OhmMapper was set to collect data once every second. Data positioning was achieved by means of a GPS. The data were collected at a slow walking pace of approximately 2 km/hr.

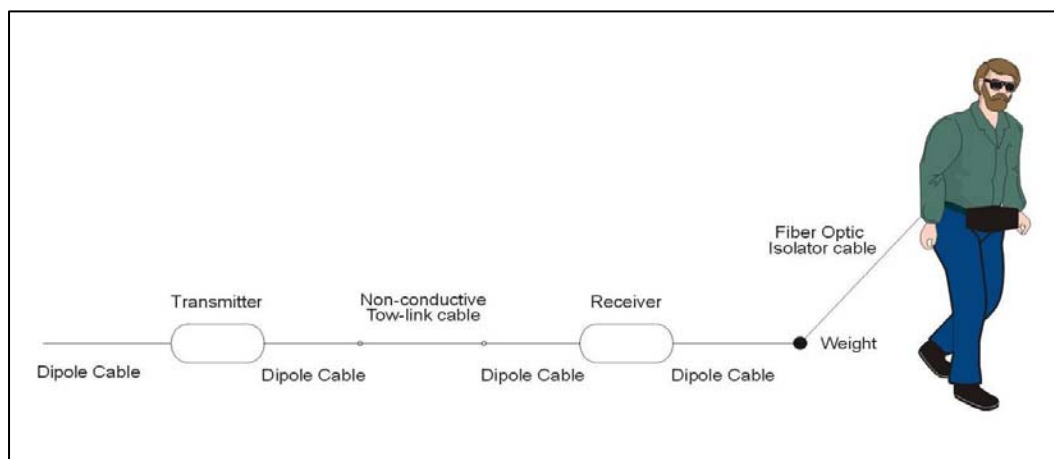


Figure 5. Illustration of the Geometrics OhmMapper capacitively-coupled resistivity system being hand-towed.

At the end of each survey, field data were transferred to a laptop computer for analysis. The data were analyzed using program MagMapper 2000 (Geometrics 2004) to ensure the proper geometry of the survey lines and fiducial markers. Program MagMapper was also used to convert the resistivity data into a format that could be directly read by program RES2DINV (Locke 2000b), a resistivity inversion program.



## Ground penetrating radar (GPR) surveys

GPR involves transmitting high-frequency EM pulses into a material. The GPR system consists of transmitting and receiving antennas. When the transmitted EM signal impinges upon the boundaries of materials with contrasting electrical properties, some of the EM signal is reflected back to the surface where it is detected by the receiving antenna. The time the signal takes to travel from the transmitting antenna, reflect off a boundary, and be detected by the receiving antenna is amplified, processed, and recorded to provide a continuous profile of the subsurface, as illustrated in Figure 6. The lack of coincidence between zero time and zero depth is due to the separation of the transmitter and receiver antenna. The first arrival at the receiver is the direct wave traveling from the transmitter to the receiver, not the reflection from the ground surface. The time span between zero time and zero depth is the one-way travel time of the direct wave between the transmitter and the receiver. The depth scale, in particular at very shallow depths, is nonlinear. The depth scale is based on the velocity of the transmitted EM pulse through the propagating media. Because a finite distance separates the transmitter and receiver antennas and the transmitted pulse has a lobe-shaped radiation pattern, the ray of the transmitted pulse that arrives at the receiver does not strike the

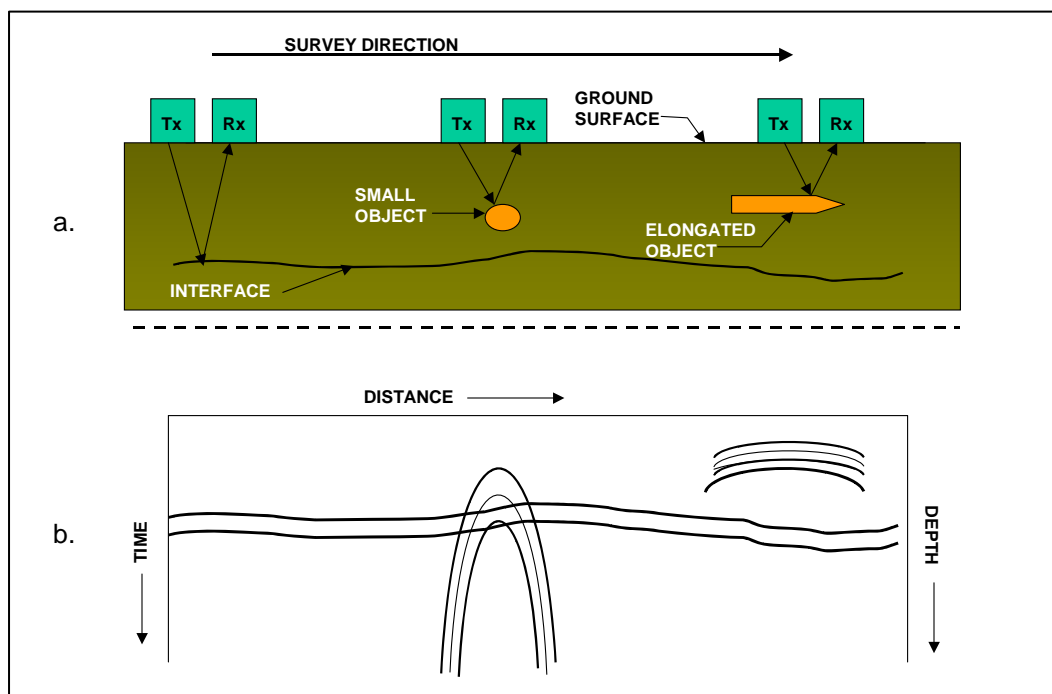


Figure 6. Illustration of GPR (a.) being towed over different shaped objects and interface and (b.) resulting GPR trace.

subsurface interface at normal incidence, but at an acute angle. The depth scale is corrected for non-normal incidence of the transmitted ray path.

The transmitted EM signals respond to changes in materials with sufficiently different electrical properties such as those caused by mineral content, salinity, water content, density, voids, etc. The depth of penetration and amount of definition that can be expected is determined by the electrical properties of the host material being tested as well as the power and frequency of the transmitting antenna. In general, the higher the conductivity of the host material is that the less the GPR depth of penetration. Different frequency antennas may be employed to obtain information from different depths. Another generality is that the lower the GPR antenna frequency used the greater depth of exploration obtained (but less resolution). On the other hand, a high frequency antenna will provide very detailed subsurface information but the depth of investigation is very small. A rule-of-thumb used for determining the depth of investigation for the GPR is:

$$d = 35/\sigma$$

where  $d$  is depth in meters and  $\sigma$  the ground conductivity in milliSiemens/m (mS/m).

The primary disadvantage of GPR is its extremely site-specific applicability. It is difficult to predict whether GPR will be successful in accomplishing its goal without prior knowledge of the electrical properties of the host materials.

The GPR systems used was a Sensors and Software Inc. pulseEkko 100 (pE 100). The pE 100 system was used with 50 and 100 MHz antennas with respective antenna separations of 2 and 1 m. The pE 100 system is a very flexible instrument in that it allows multiple antenna separations and orientations, modes of operations, and system parameters to be used. System parameters are input and controlled from a digital video logger (DVL). As the data are being collected a profile of the subsurface is displayed on the DVL screen. Figure 7 shows the pE 100 system with the 100-MHz antennas. Figure 8 shows the pE 100 GPR control unit and DVL mounted on a cart.

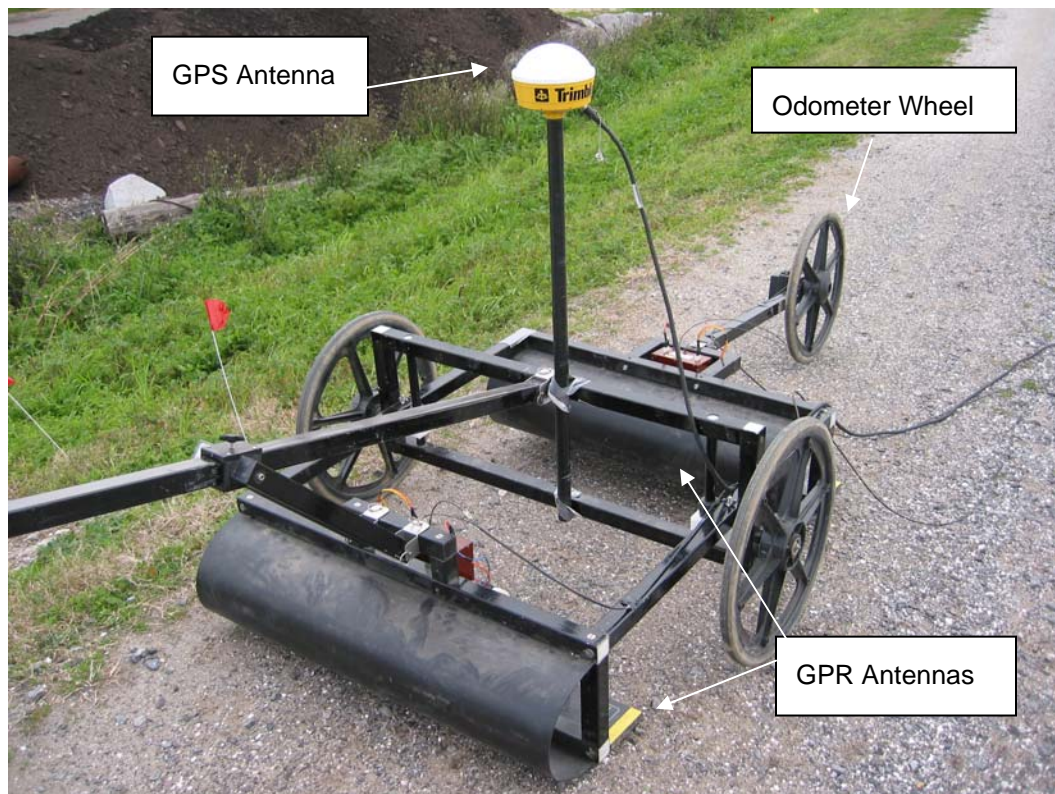


Figure 7. Sensors and Software pE 100 GPR system with 100-MHz antennas.

The GPR cart was pulled along survey lines at a very slow walking rate (approximately 1.5 to 2.0 km/hr). A Trimble AG-132 GPS was used to obtain positioning information. The cart's odometer wheel was used as a back-up positioning system. The GPR and GPS information were simultaneously recorded by the GPR's DVL and transferred to a computer at the end of the survey.

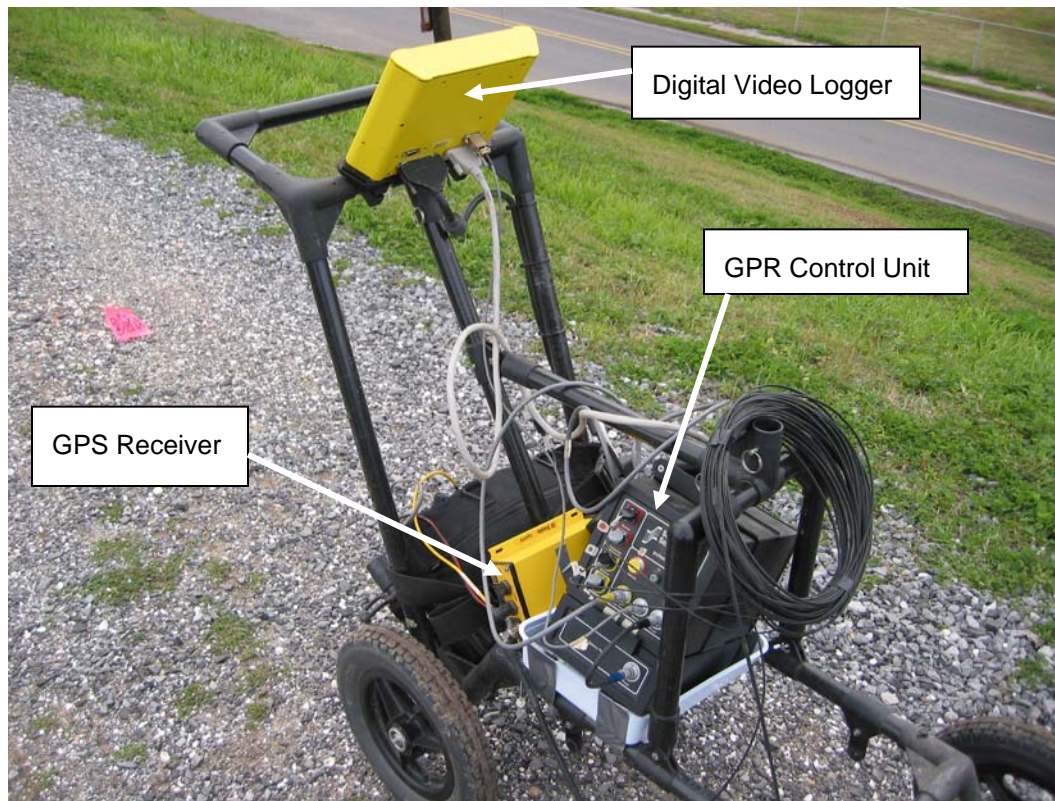


Figure 8. Cart-mounted pE 100 control unit and DVL.

### 3 Geophysical Test Results and Interpretation

This section describes each of the three test sites and presents survey results. Capacitively-coupled resistivity surveys were conducted at each site using several n-spacings, but the data were too noisy to yield any useful information and the results are not presented here.

#### Site 1

Site 1 is located on the Sacramento River east (left) bank levee from just south of the intersection of Sankey Road and Garden Highway approximate LM 0.1 to approximate LM 1.2 (Figure 9). The geophysical surveys were run along the landside of the toe of the levee. The site is located in a rural area adjacent to farmland. The length of the survey line is approximately 1,700 m. The north and south ends of the line correspond to approximate UTM coordinates (621408, 4293254) and (622253, 4291749), respectively. Several cultural features located adjacent to the site were noted. These include powerlines, a steel-welded wire fence, a barn with steel roofing, and several concrete irrigation-control structures. Figures 10 and 11 show some of the cultural features adjacent to the survey line. Appendix A presents soil profiles along the levee alignment and 30 m from the toe of the levee for Site 1.

#### Electrical conductivity surveys

The results of the electrical-conductivity surveys using the EM31 and EM34 and conducted along the landside toe of the levee are presented in Figure 12. EM31 data range between roughly 10 and 15 mS/m along the length of the survey line and show little variability. These are relatively low conductivity values and may indicate coarser-grained and/or dryer soil in the upper 5 m. The EM34 data indicate conductivity values ranging between approximately 40 and 65 mS/m along the survey line. In general, the data from the 20-m spacing have approximately the same or slightly greater conductivity values than the data from the 10-m spacing. Both sets of EM34 data indicate much higher values than those obtained from the EM31. Since the EM34 investigates to greater depths than the EM31, the higher conductivity values from the EM34 surveys suggest that deeper soils have a higher clay content. The higher EM34 readings near the





Figure 9. Plan view of survey line, Site 1.



Figure 10. Metal fence located adjacent to survey line, Site 1.



Figure 11. Barn with metal roof adjacent to survey line, Site 1.

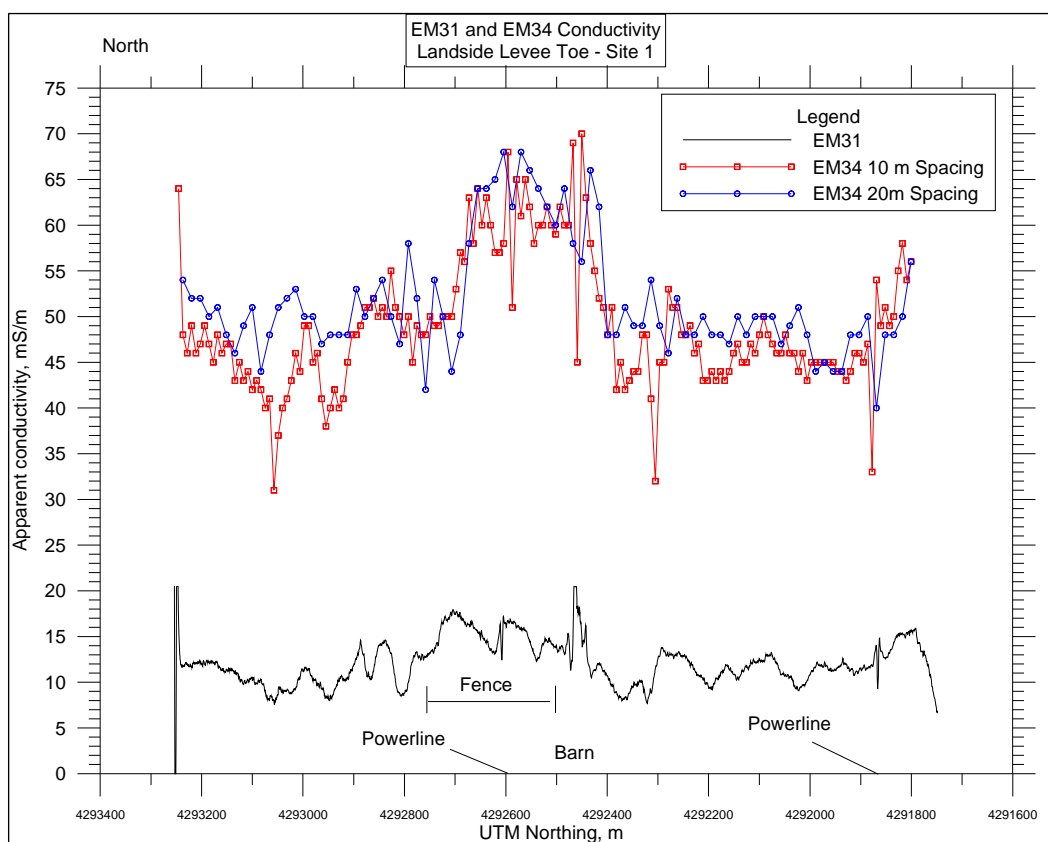


Figure 12. Electrical conductivity surveys, Site 1, landside toe.

middle of the survey line may be caused by an increase in clay content and/or by the proximity of a steel-welded wire field fence and a barn. The soil borings for this area (Appendix A) show that this is an area composed predominantly of clayey materials, which agree with the EM34 results.

### GPR surveys

GPR surveys were conducted along the entire length of the survey line using antenna frequencies of 100 and 50 MHz. Appendixes A and B present the results of the 100-MHz and 50-MHz GPR surveys, respectively. Both GPR antennas had relatively shallow depths of investigation with the 50-MHz and 100-MHz antennas penetrating to depths of approximately 2 and 3 m, respectively. Several hyperbolic targets, visible in both data sets at approximate two way times of 80 ns, are presumed to be caused by radar signals being reflected from overhead powerlines. Other surface features, for instance a barn adjacent to the GPR survey line at approximate Sta. (621913,4292461), also reflect radar energy and appear as anomalies in the data.



## Site 2

Site 2 is located on the Sacramento River east (left) bank levee from a point approximately 350 m north of Elverta Road to Reservoir Road (approximate LM4.9 to LM6.1) as shown in Figure 13. The length of the survey line is approximately 1,700 m. The north and south ends of the line correspond to approximate UTM coordinates (621277, 4286309) and (620080, 4284795), respectively. The geophysical surveys were run along the landside of the toe of the levee. The site is located in a rural area adjacent to farmland and orchards. Several cultural features were located adjacent to the site. These include Elverta Road, parked vehicles, drive-ways, and powerlines. Figure 14 shows a portion of the survey line at Site 2 illustrating one of the cultural features that can influence survey results. Soil profiles prepared for Site 2 along the levee alignment and 30 m from the toe of the levee are shown in Appendix D.

### Electrical conductivity surveys

The results of the EM31 and EM34 electrical conductivity surveys conducted at Site 2 are shown in Figure 15 and are strikingly different from those obtained at Site 1. Whereas at Site 1 where there was a significant difference in values between the EM34 and EM31, the data from Site 2 indicate very similar values. Also, whereas the data from Site 1 show fairly consistent values across the entire site, the Site 2 data show significant differences in values from one end of the survey line to the other. In general, the Site 2 EM31 and both EM34 surveys indicate the same trends: an increase in average electrical conductivity values from approximately 40 to 50 mS/m (indicating an increase in fine-grained materials) between UTM northing coordinates 4286300 and 428600 and then a gradual decrease in conductivity to about 5 to 10 mS/m (indicating an increase in coarse-grained material) to the south end of the line. Referring to the boring logs of this site (Appendix D) clay materials are found at the northern end of the site near Elverta Road. The borings at the south end of the site near Reservoir Road indicate predominantly sandy materials which correspond with the low conductivity EM survey values. The EM34 20-m-spaced survey, in general, has the lowest conductivity value at each test location with the exception occurring near the south end of the line where it has about the same value as the EM31 and EM34 10-m-spaced surveys. This indicates an increase in coarser-grained materials as a function of depth for the northern portion of the site and less of a change as a function of depth at the south end of the line. A significant decrease in conductivity values



Figure 13. Geophysical survey line layout, Site 2.

occurs at approximate UTM northing station 4285800 that is not related to any visible surface features. This anomalous feature is caused by coarse-grained materials such as sands and/or gravels.

### GPR surveys

GPR surveys were conducted along the entire length of the survey line using a 100-MHz antenna. A 50-MHz survey was attempted, however, a few meters into the survey the GPR cart broke down and GPR surveying was discontinued. The results of the 100-MHz survey conducted at Site 2 are shown in Appendix E. As was the case at Site 1, the 100-MHz data have a depth of penetration on the order of 2 m. Again, several hyperbolic targets are visible at two-way times greater than 70 ns and are presumed to be caused by radar signals being reflected from overhead powerlines



Figure 14. A portion of the geophysical survey line, Site 2.

and other surface features. The area of disturbance between approximate Sta. (621120, 4286030) and (621080, 4285977) is the area that corresponds with the location of Elverta Road. Because of the GPR's shallower depth of penetration, no significant changes in GPR signal from the north end to the south end of the survey line are apparent that are comparable to the changes shown in the EM surveys.

### Site 3

Site 3 is located on the Sacramento River east (left) bank levee from approximately 450 m south of the location where Interstate Highway 5 and the levee intersect and continues in a southerly direction for approximately 3,300 m (approximate LM9 to LM11) as shown in Figure 16. The geophysical surveys were run along the landside of the toe of the levee. The north and south ends of the line correspond to approximate UTM coordinates (619990, 4281151) and (622171, 4278719), respectively. The site is located in a rural environment adjacent to farmland. Several cultural features are located adjacent to the site with the potential to cause interference with the EM surveys. These include chain link and metal fences (Figure 17), buildings (Wildrose Farms), private residences (Figure 18),

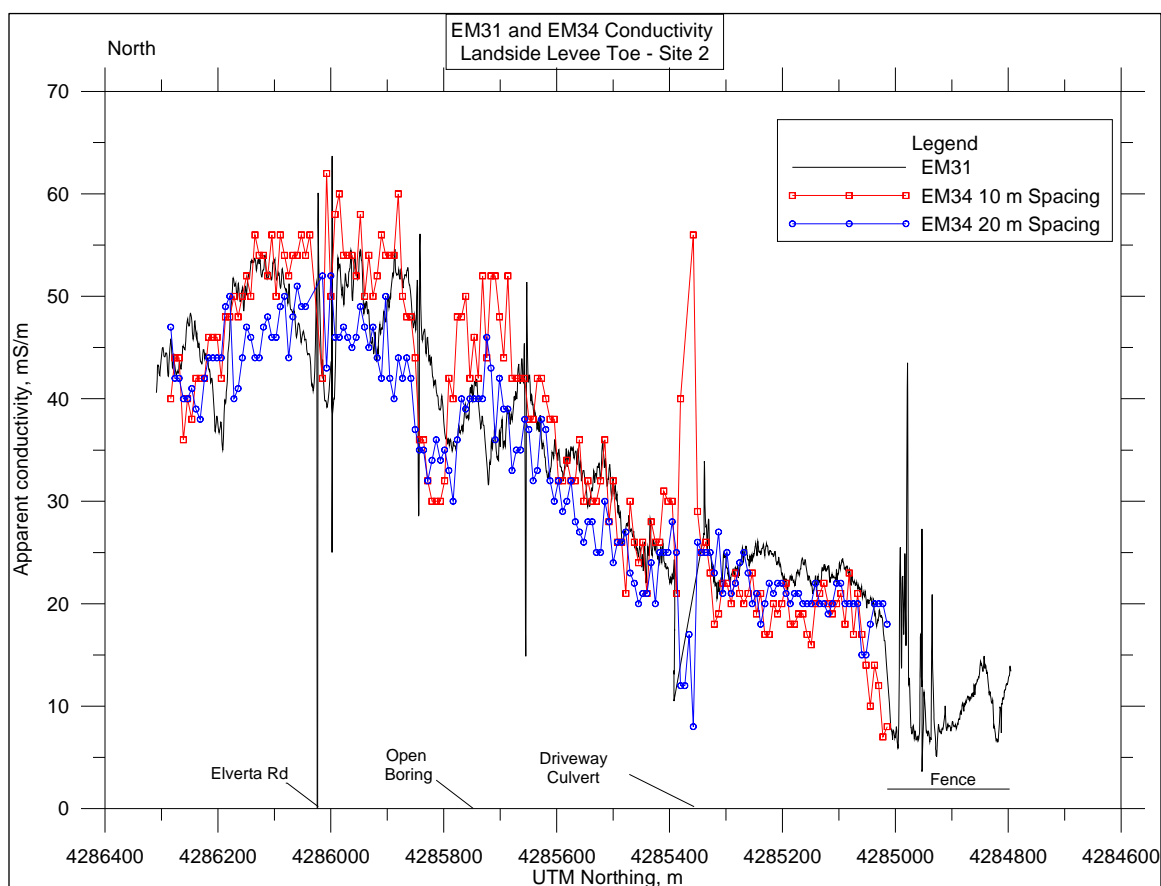


Figure 15. Electrical conductivity surveys, Site 1, landside toe.

reinforced concrete irrigation towers, metal irrigation piping, gravel drive-ways, and overhead powerlines. Soil profiles along the levee alignment and 30 m from the toe of the levee for Site 3 are shown in Appendix F.

The results of the conductivity surveys are presented in Figure 19. As was the case for Site 2, the three EM surveys show the same general data trends. The results of the three survey lines also show a general decrease in conductivity from approximately 30 to 15 mS/m between approximate UTM northings of 4281150 and 4280600. This indicates that the soil at the north end of the line is silty and gradually increases in sand content to the south along this survey section. In this section of the survey line, the three EM surveys show a similar trend and have very similar conductivities. This shows that the soil type in this area probably does not vary much as a function of depth. Between approximate northings 4280600 and 4280200, the readings for the three surveys show large fluctuations. The survey line in this area runs along about 20 m of chain link fence, along about 280 m of a fence constructed with steel pipes, along





Figure 16. Geophysical survey line layout, Site 3.

a private residence, over a gravel drive, and directly beneath power lines. These cultural features have a marked effect on the conductivity readings. It is presumed that the data in this area are not valid for making any inferences of soil type. No visible surface features were noted between approximate northings 4280200 and 4279900 that could explain the rather high conductivity values in this portion of the survey line. It may be possible that these anomalously high readings are caused by a buried pipeline oriented parallel to the survey line since the anomalous readings return to normal at the location of a concrete irrigation structure. Between



Figure 17. Steel pipe fence adjacent to survey line between approximate UTM northings 4280480 and 4280380, Site 3.



Figure 18. Private residence adjacent to survey line, approximate UTM northing 4280250, Site 3.



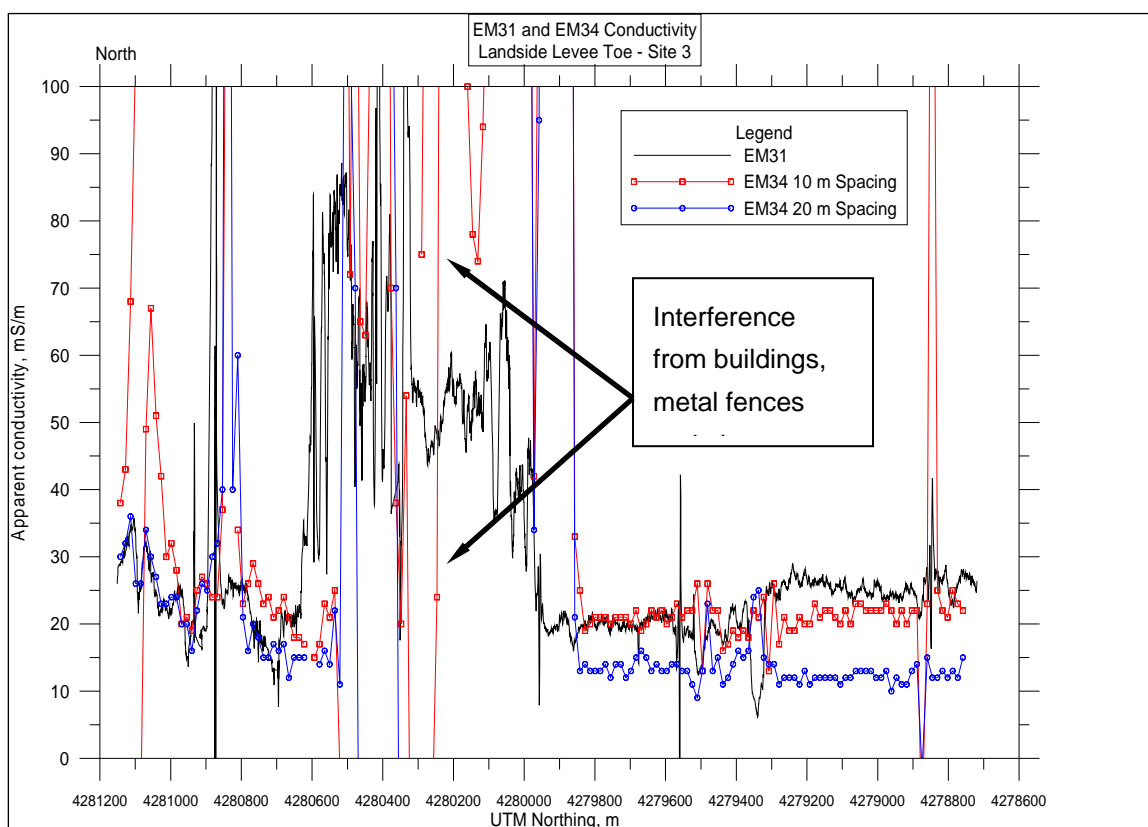


Figure 19. Electrical conductivity surveys, Site 3, landside toe.

approximate northing 4279900 and the south end of the line, the three surveys indicate fairly constant readings. The EM31 shows the highest average readings (20 to 25 mS/m) and the EM34 20-m-spacing survey showing the lowest readings (10 to 15 mS/m). The 20 to 25 mS/m readings from the EM31 and EM34 10-m-spacing survey are interpreted as being caused by predominantly silty-sandy material in the upper 15 m with the amount of sand increasing with depth. The 10 to 15 mS/m values obtained from the EM34 20-m-spacing survey indicates that down to an approximate depth of 30 m the soil is chiefly sand.

The soil borings of this area (Appendix F) show that the soils consist chiefly of sands and silts and that sand increases as a function of depth. This agrees well with the EM survey results. Two borings, 2F-01-58 and 2F-01-59, located at approximate LM 9.5, show predominantly clay in the upper 9 to 12 m. These borings are in the vicinity where the survey line passes by some interfering cultural features. Consequently, the EM survey values in this area cannot be correlated to these two borings.

## **4 Summary, Conclusions, and Recommendations**

### **Summary and conclusions**

A series of geophysical surveys was conducted along three reaches of the Sacramento River levee north of Sacramento, CA, during the period 14-24 July 2004. The purpose of this study was to determine the potential of rapidly assessing levee foundations using geophysical methods. The information obtained from such surveys could then be used to supplement geologic data between existing borings. The study was funded by the TOWNS Research Program.

The three test sites were located on the east side of the Sacramento River between the Natomas Cross Canal and Powerline Road and were between 1,700 and 3,300 m in length. The materials underlying the site are alluvial in nature and consist of clay, silt, sand, and gravel. Three survey methods were used to infer soil type: electromagnetic (EM) induction, capacitively-coupled electrical resistivity, and ground penetrating radar (GPR).

The Geometrics OhmMapper capacitively-coupled electrical resistivity system used for this study exhibited an abnormally high amount of noise which made the data unusable. This was rather unfortunate because this method could have provided a 2-dimensional representation of the electrical conductivity (vertical cross section). Recent software and hardware updates of this system since the time of this study have improved the data quality and increased data collection efficiency.

A pulseEKKO GPR with 50- and 100-MHz antennas was used over two of the three sites. The depth of investigation for the GPR is limited to approximately the upper 3 m in this geologic environment. GPR may be useful for detailed mapping of the very shallow (upper 2 to 3 m) subsurface but is not of much use for mapping deeper geologic targets.

The combination of the two Geonics Ltd. EM conductivity meters (Geonics EM31 and EM34 conductivity meters) provided useful electrical conductivity data which could be used to deduce soil type along the survey line. In general, high conductivity values are associated with clayey materials



whereas lower conductivity values suggest the presence of more sandy or coarser-grained soil. Also, since the two different EM instruments have different depths of investigation, inferences about changes in material type as a function of depth can be made. The conductivity data from the three test sites show different results. The differing EM results are caused by changes in material type as apparent in the soil borings from the each test site. Site 1 is characterized as having constant relatively high conductivity values across the site that correspond to clayey materials in the soil profile (see borings in Appendix A). Site 2 has a gradual decrease in conductivity values from north to south that corresponds to a decrease in clayey materials from north to south in the soil profile (see borings in Appendix D). Site 3 has consistent relatively low conductivity values along the entire survey line with the exception occurring in the vicinity of a steel fence, some residences, and a suspected buried pipeline where the readings were affected by these features and characterized by extremely high and erratic values. The boring logs for this site show mainly silty-sandy material in the near-surface and the amount of sandy material increasing with depth. The one boring that showed clayey material occurred in the area where the conductivity data was masked by the nearby cultural features.

On the basis of the comparison of EM conductivity values and boring information it is concluded that EM data can be related to soil type. The EM survey method can provide useful information between borings. In areas where soil borings do not exist, EM conductivity data can be useful for planning and strategically placing future soil borings. The EM34, as used in this survey, works well at showing the locations of conductivity features along a survey line but is limited to using a rule-of-thumb relationship for estimating depths to features.

## Recommendations

Based on the results of this investigation, the following recommendations are made:

- Conduct further studies using the EM34 with 10-, 20-, and 40-m inter-coil separations. The EM34 should be programmed to collect in continuous mode and vehicle-towed. A GPS should be used to provide positional information. These data should provide soils data to a maximum depth of approximately 60 m.

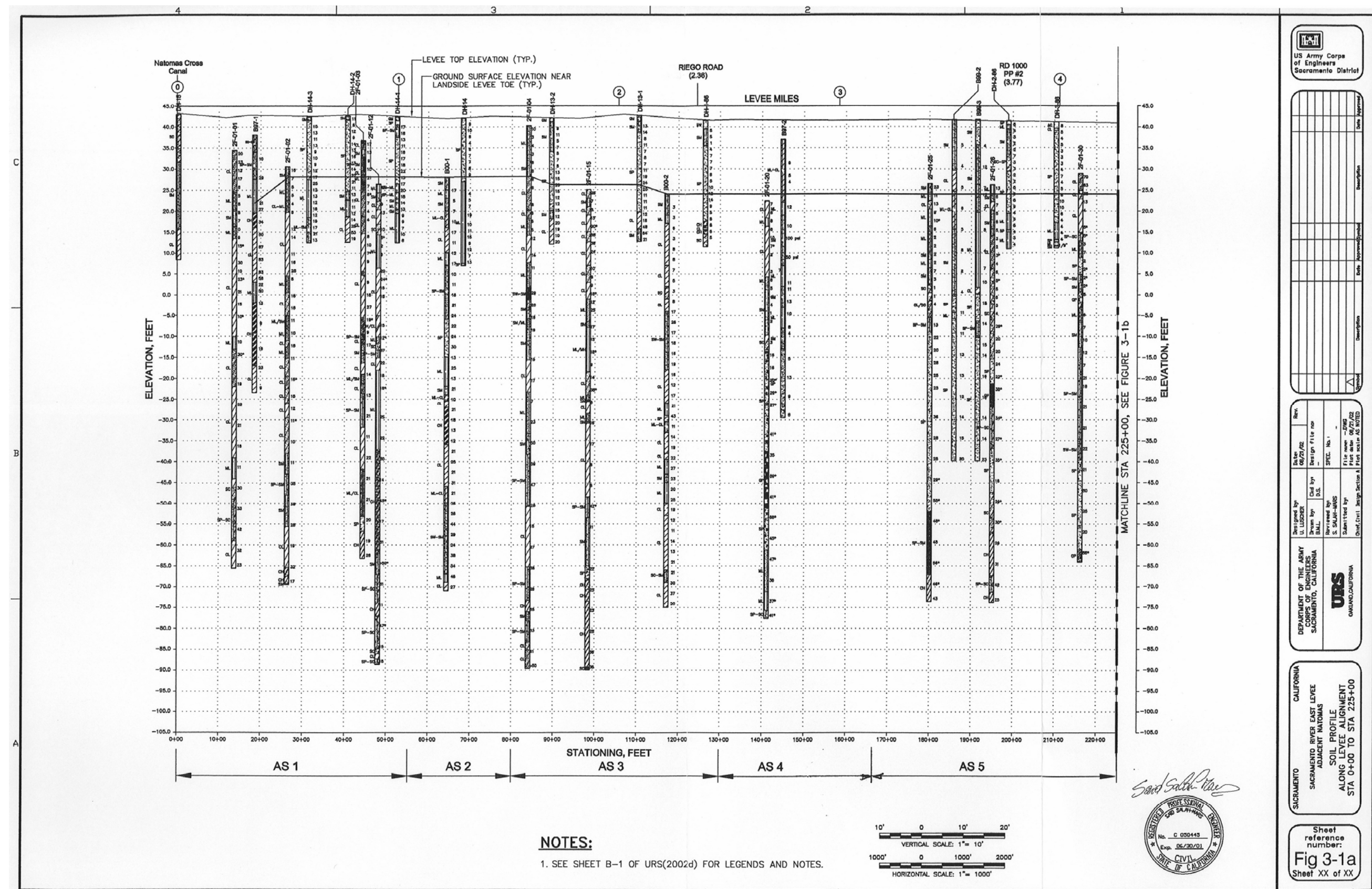
- EM31 surveys should be run to obtain soil information for the upper 4.5 m of material. These data can provide information regarding variations in thickness of the top stratum.
- Perform further studies using a Geometrics capacitively-coupled resistivity system (OhmMapper) to determine depth of exploration capabilities and to provide resistivity depth sections. If this instrument has sufficient depth of exploration it could provide very good resistivity information laterally as well as a function of depth.
- Perform DC resistivity profile surveys in selected locations to calibrate EM results. The DC resistivity method has been successfully employed for decades for obtaining soil resistivity depth sections. The drawback to this method is that it is labor-intensive because electrodes have to be hammered into the ground surface along the length of the survey line at predetermined distances.

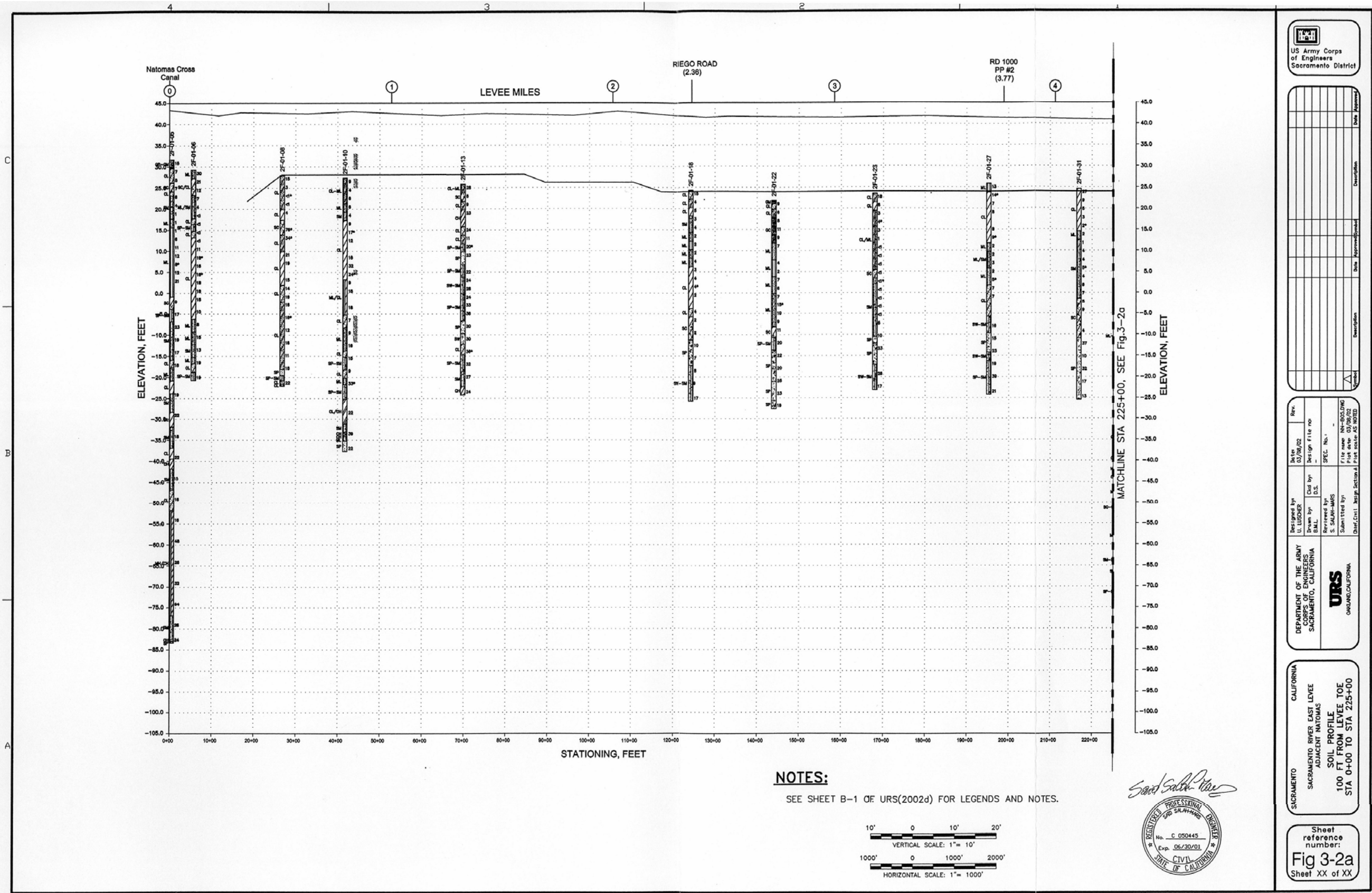
It is recommended that all soil borings be georeferenced within a survey area. Most of the boring information that exists is referenced to stationing, river miles, or to a Reclamation District's levee mile designation, making it difficult to compare the geophysical data with the boring data.

## References

- California Division of Water Resources (DWR). 1955. Seepage conditions in Sacramento Valley; report to the Water Budget Authority. Sacramento, CA.
- Dunbar, J.B., R. F. Ballard, W. L. Murphy, T. E. McGill, J. L. Llopis, L. D. Peyman-Dove, and M. J. Bishop. 2003. *Condition assessment of the U.S. International Boundary and Water Commission, Lower Rio Grande Valley levees, south Texas*. Volume I, Main Text and Appendices, ERDC TR-03-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Geometrics. 2004. MagMap 2000 (computer program). [www.geometrics.com](http://www.geometrics.com).
- Hess, J. R., and G. L. Sills. 2004. A review of Corps of Engineers levee seepage practices in the central California flood control system. In *Proceedings 24th Annual USSD Conference, Working Rivers—Balanced Resource Management, St. Louis, MO*.
- Keller, G. V., and F. C. Frischknecht. 1966. *Electrical methods in geophysical prospecting*. Oxford: Pergamon Press Inc.
- Locke, M. H. 2000a. Electrical imaging surveys for environmental and engineering studies, Lecture notes. <http://www.geoelectrical.com/>.
- Locke, M. H. 2000b. RES2DINV, Rapid 2D resistivity and IP inversion (computer program). Distributed by IDS Scintrex, Concord Ontario, Canada.
- Marchand, D. E. and A. Allwardt. 1981. *Late Cenozoic stratigraphic units, northeast San Joaquin Valley, California*. U.S. Geological Survey Bulletin 1470.
- Reid, R. L. 2005. Is California next? ASCE, *Civil Engineering Magazine* 75(11):39-47, 84-85.
- URS (2002). Final supplemental geotechnical report for reach north of Powerline Road, prepared for U.S. Army District, Sacramento, under subcontract to Montgomery Watson Harza, 6 December.

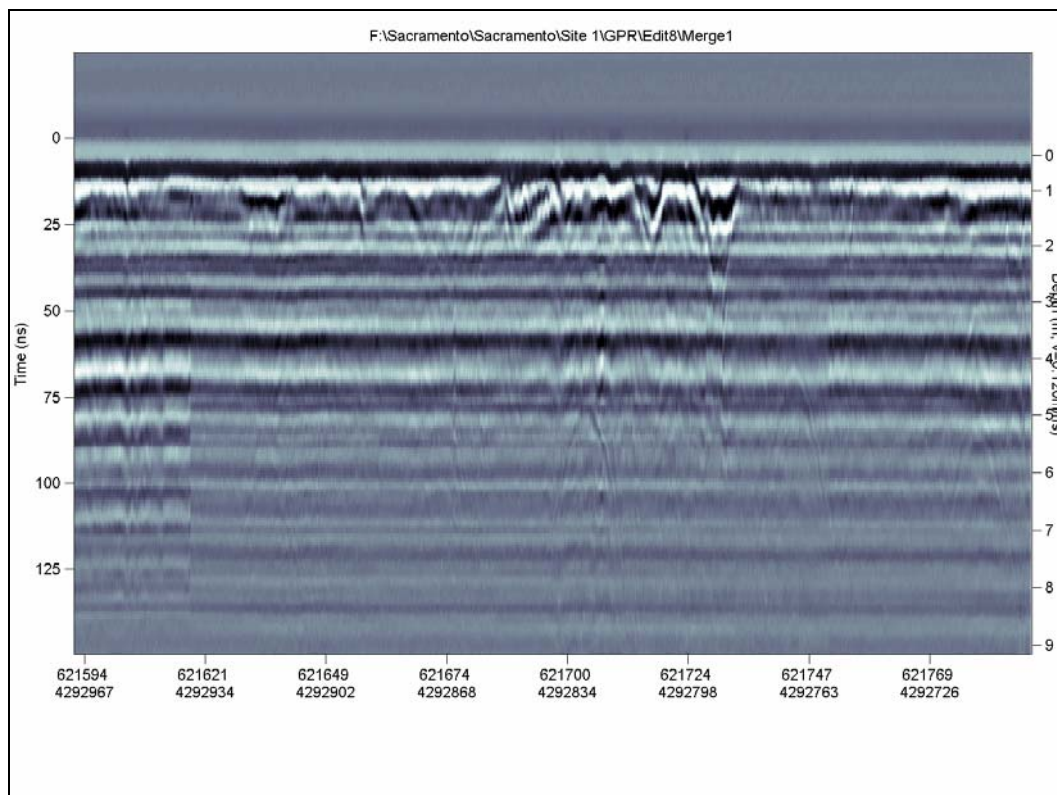
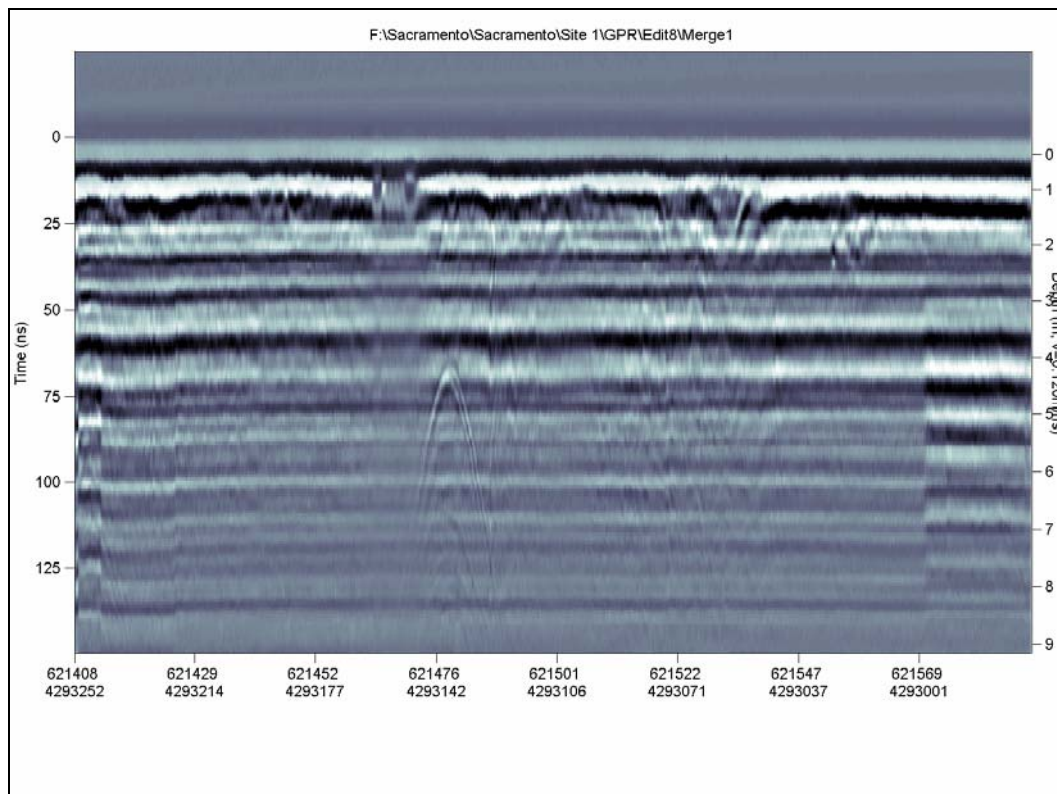
## **Appendix A: Soil Profiles, Site 1**

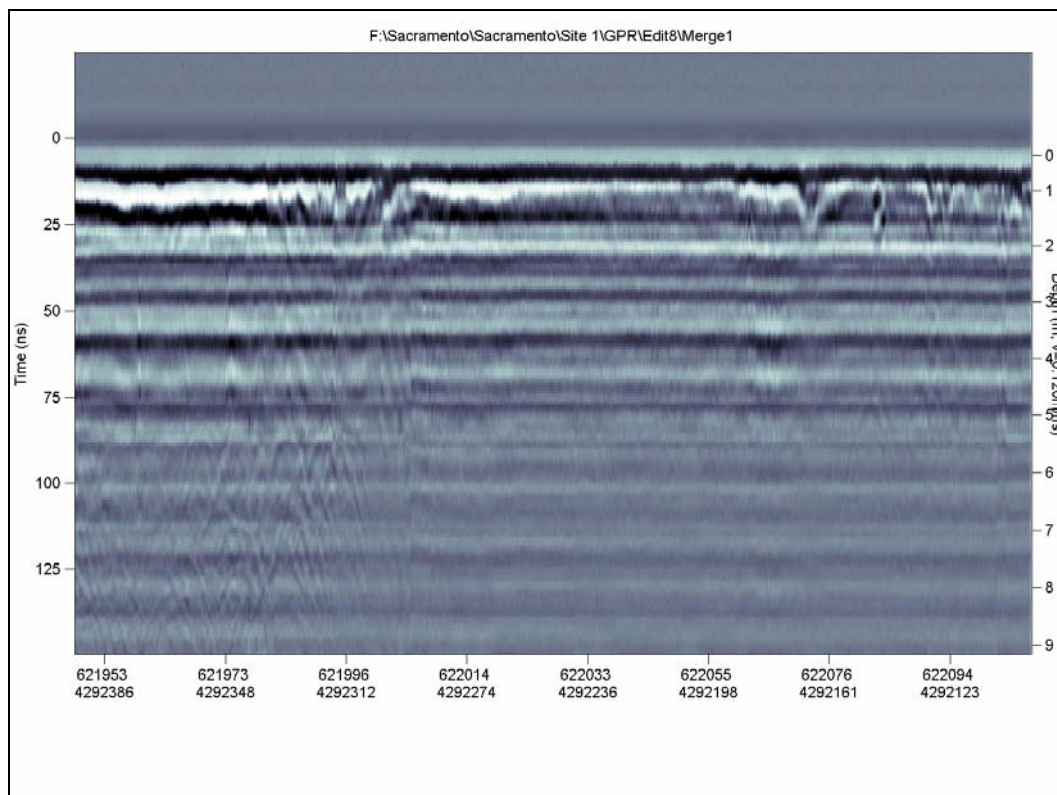
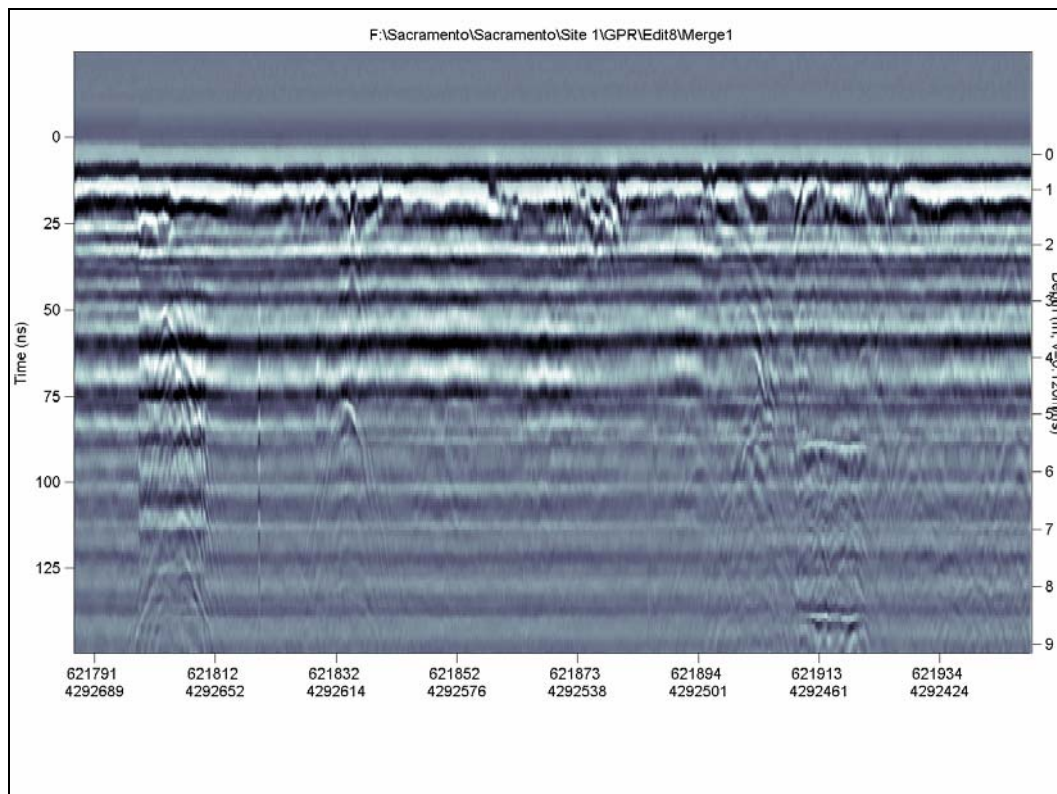


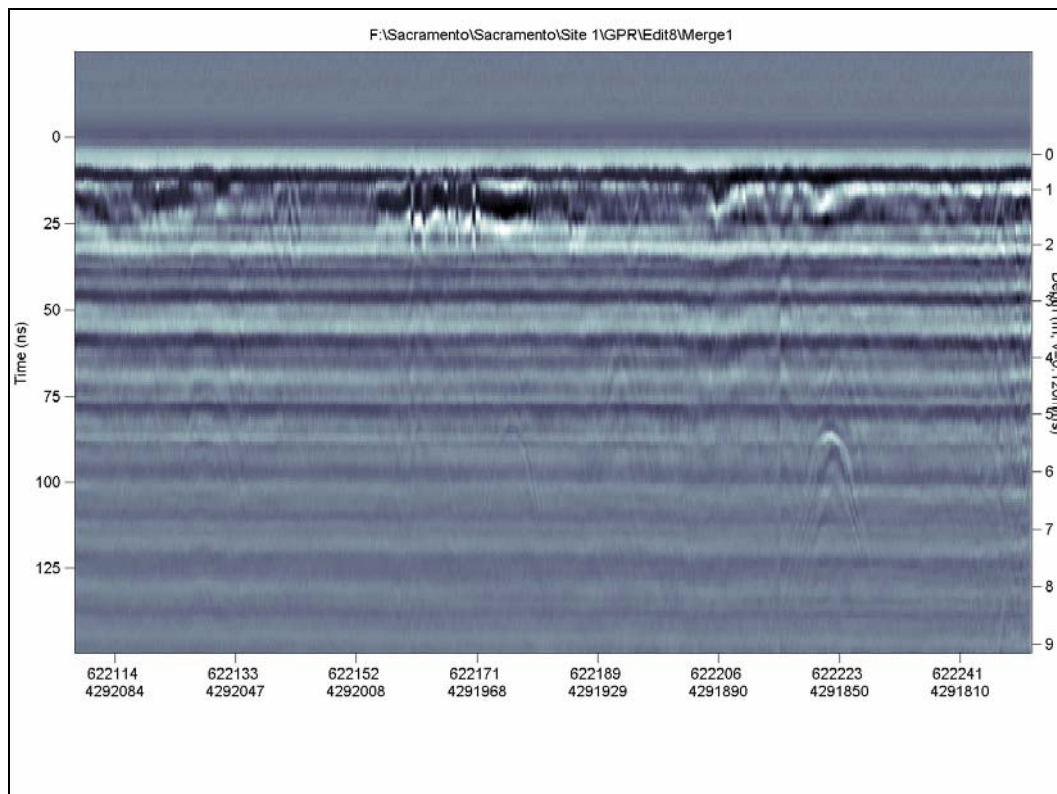




## **Appendix B: GPR Records, 100 MHz, Site 1**

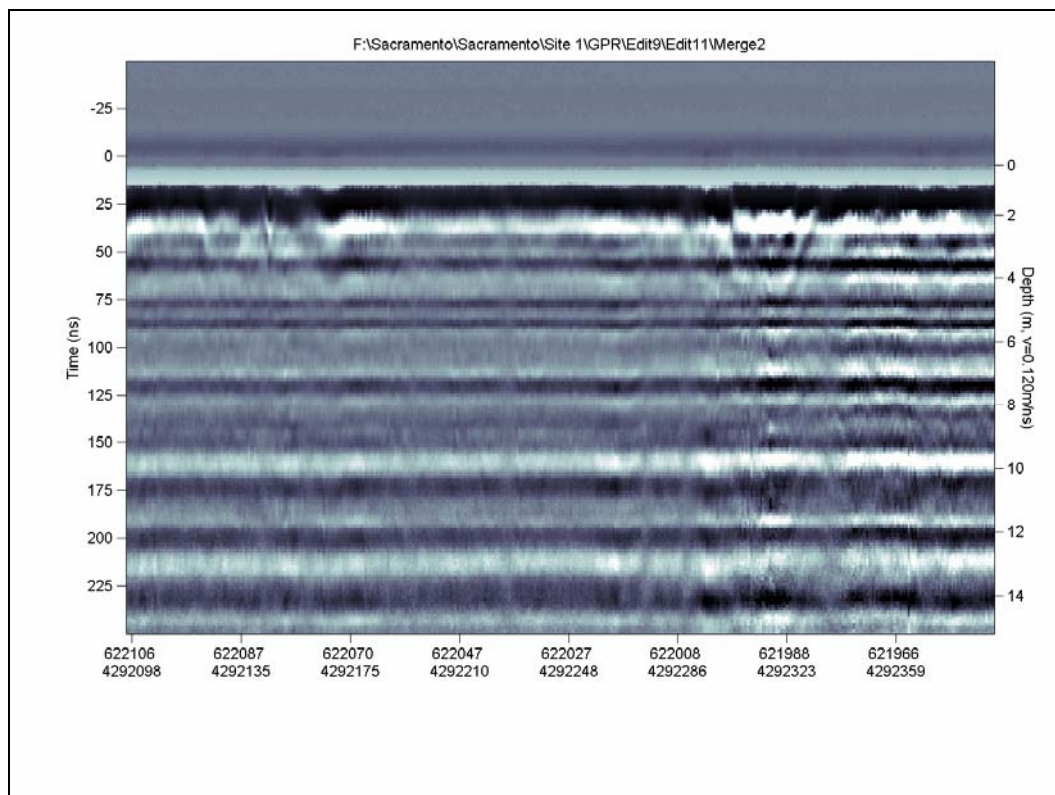
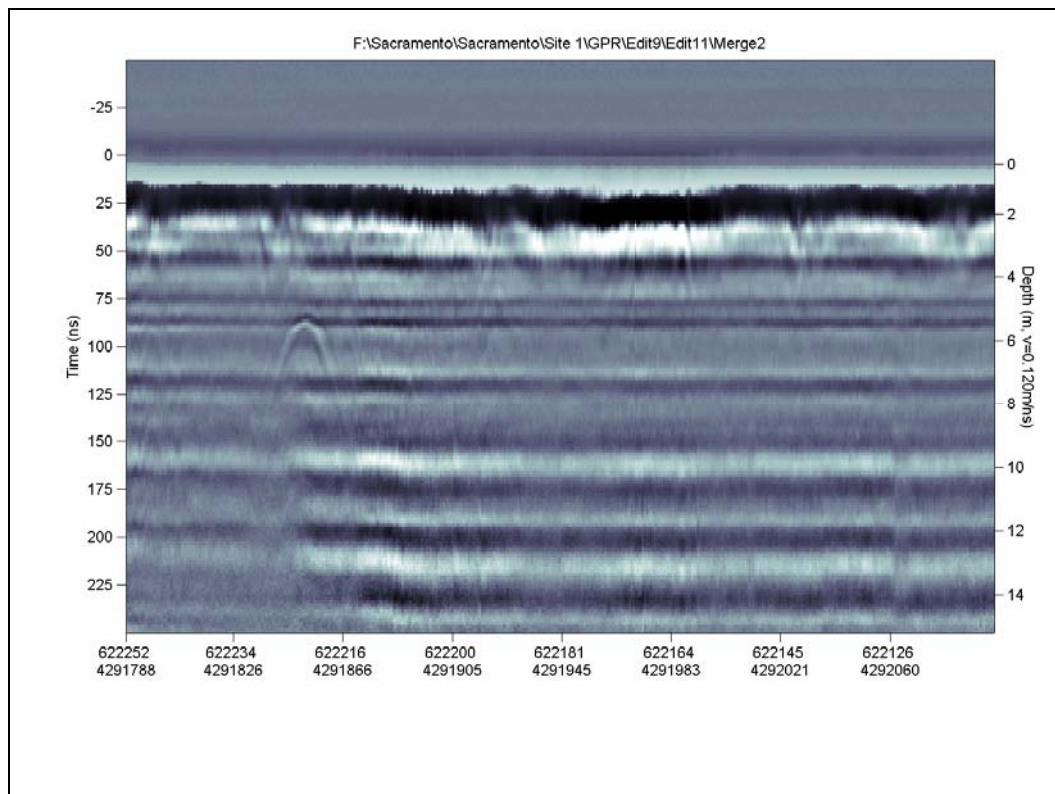


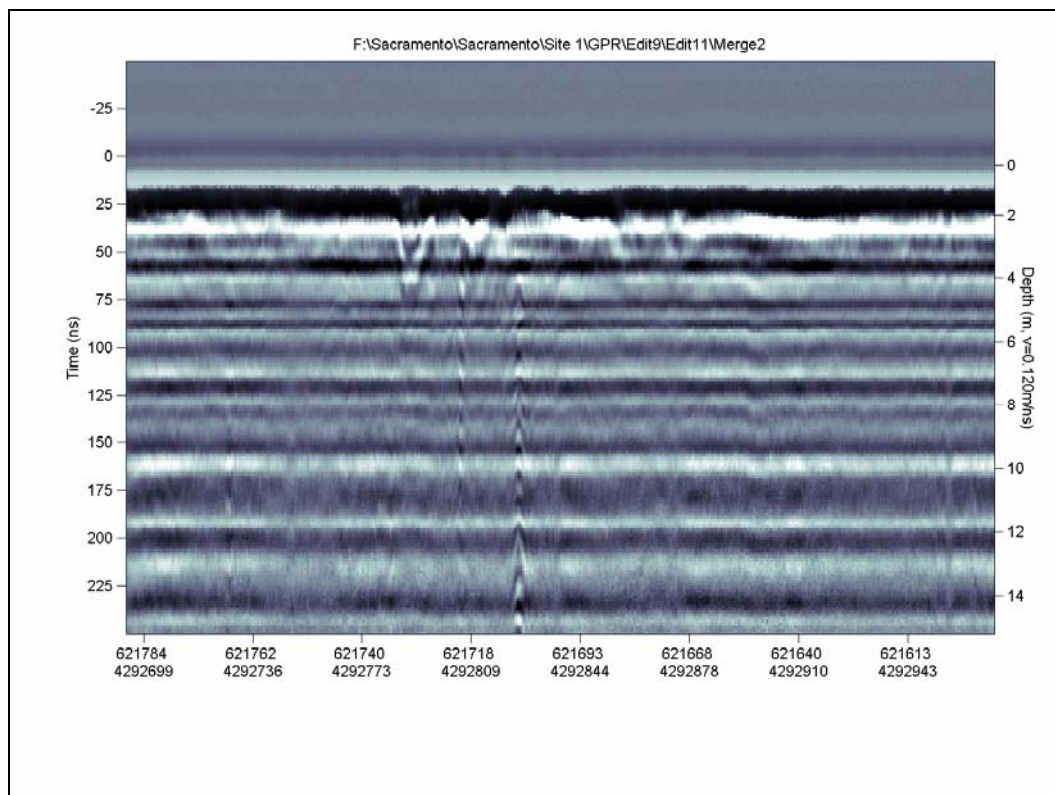
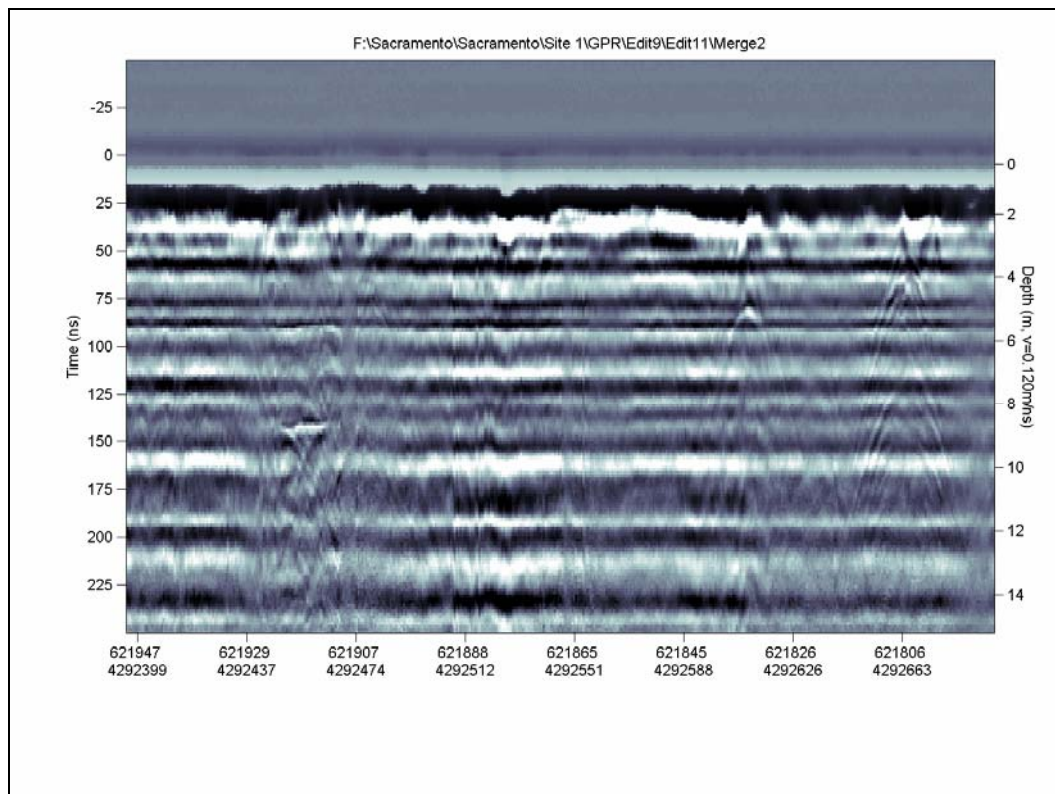


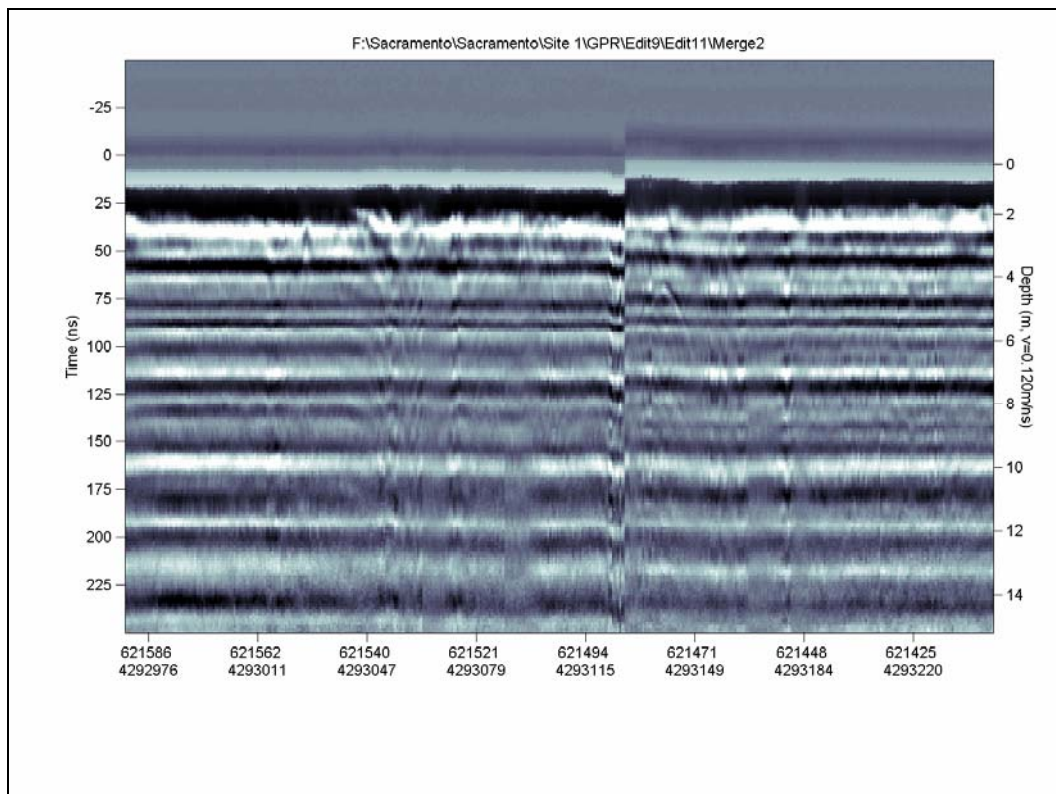


## **Appendix C: GPR Records, 50 MHz, Site 1**



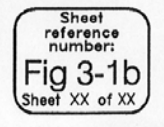




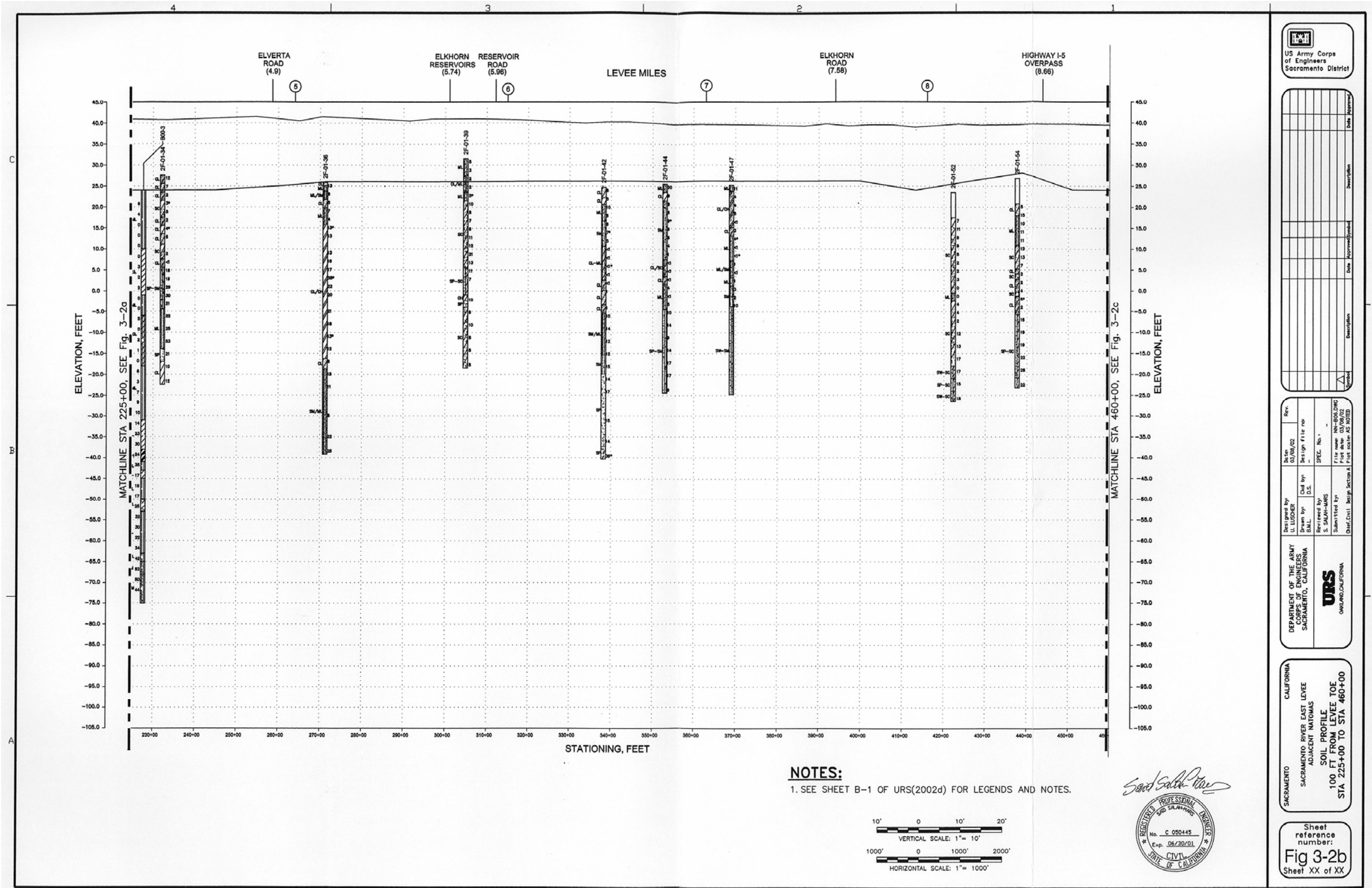


## **Appendix D: Soil Profiles, Site 2**

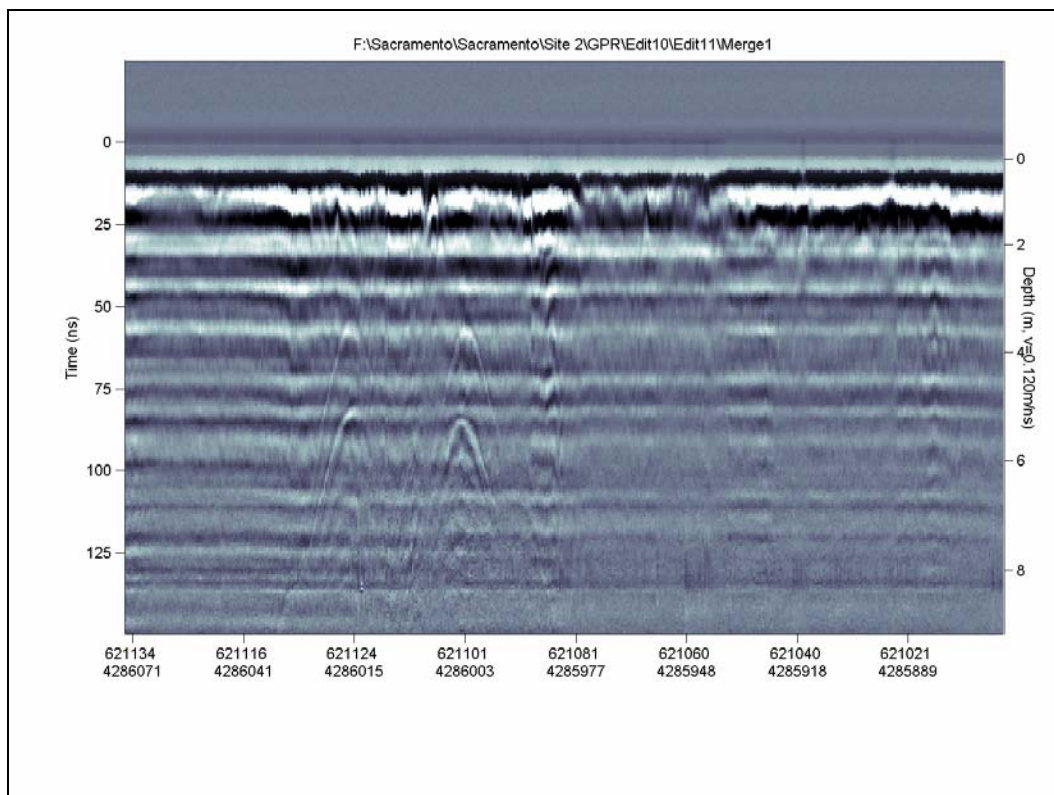
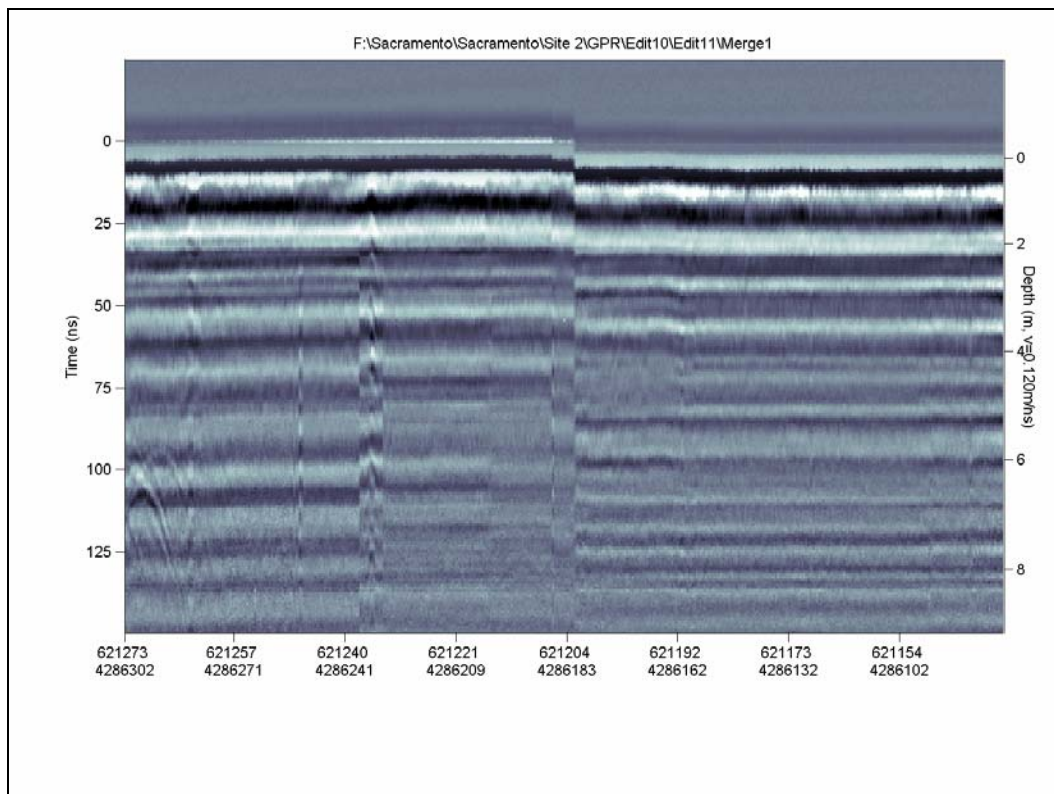




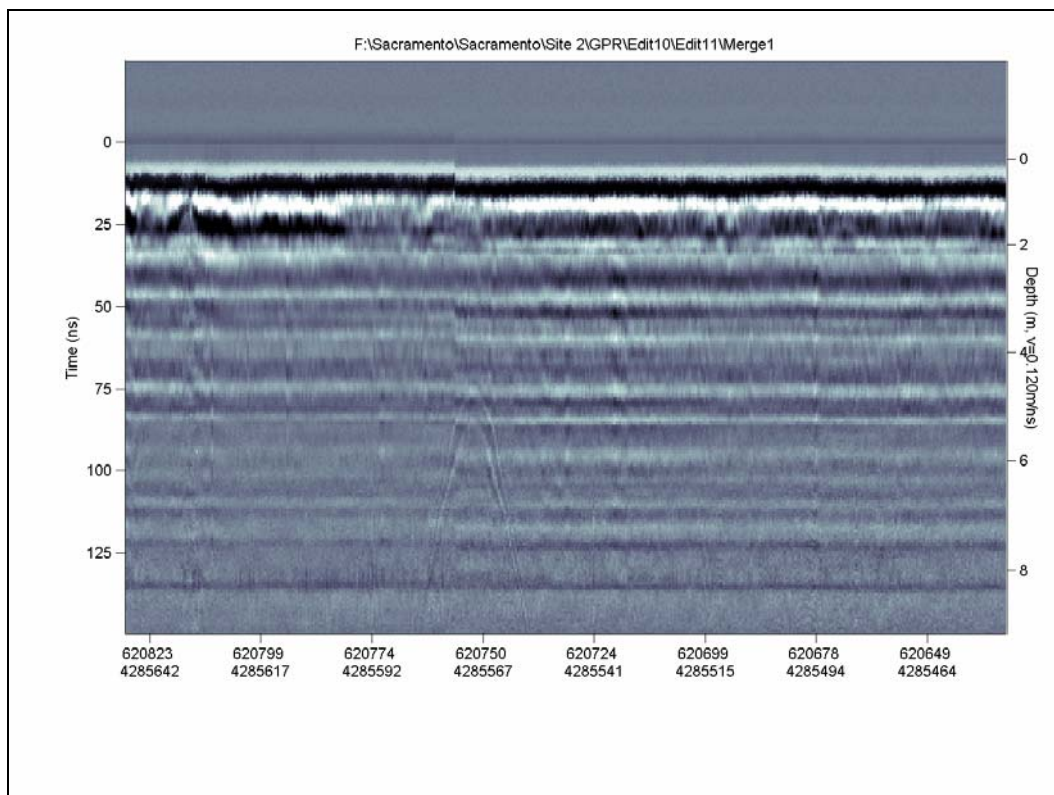
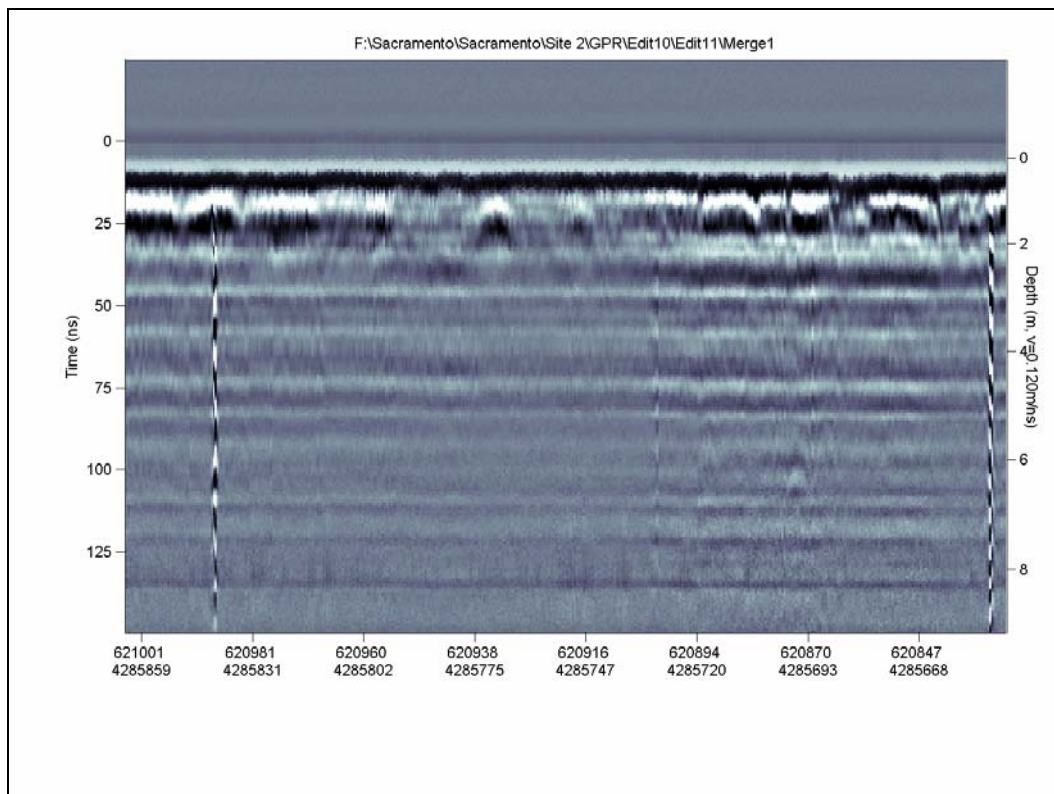


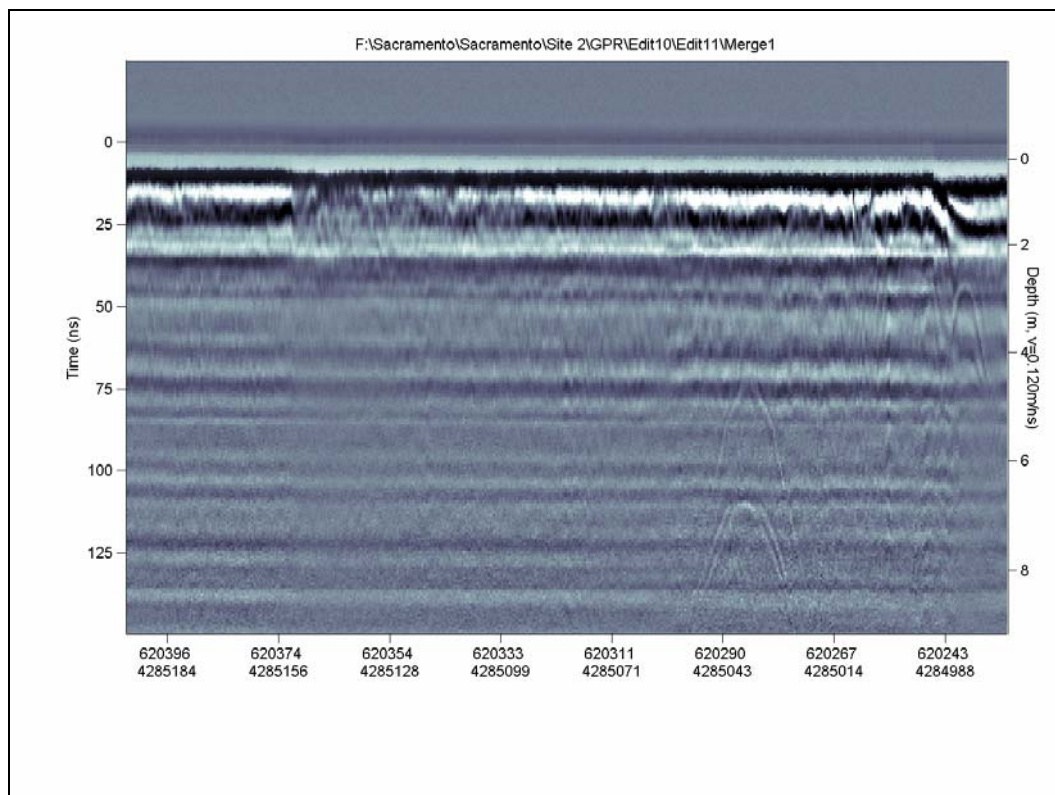
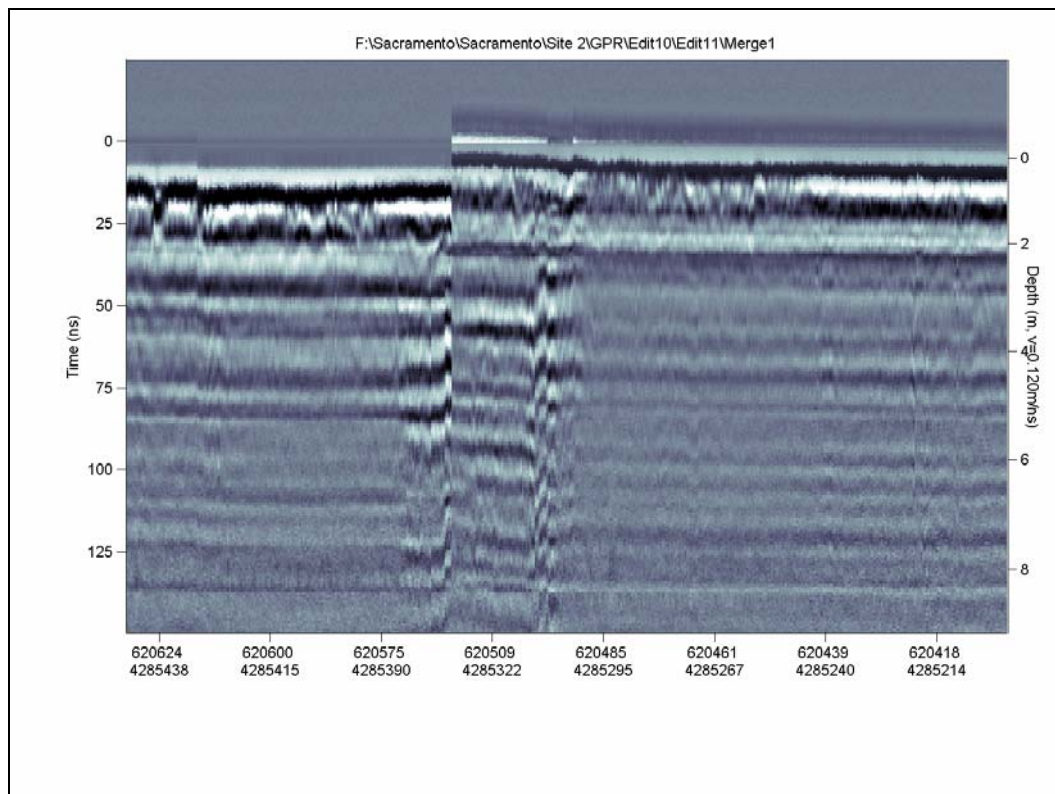


## **Appendix E: GPR Records, 100 MHz, Site 2**



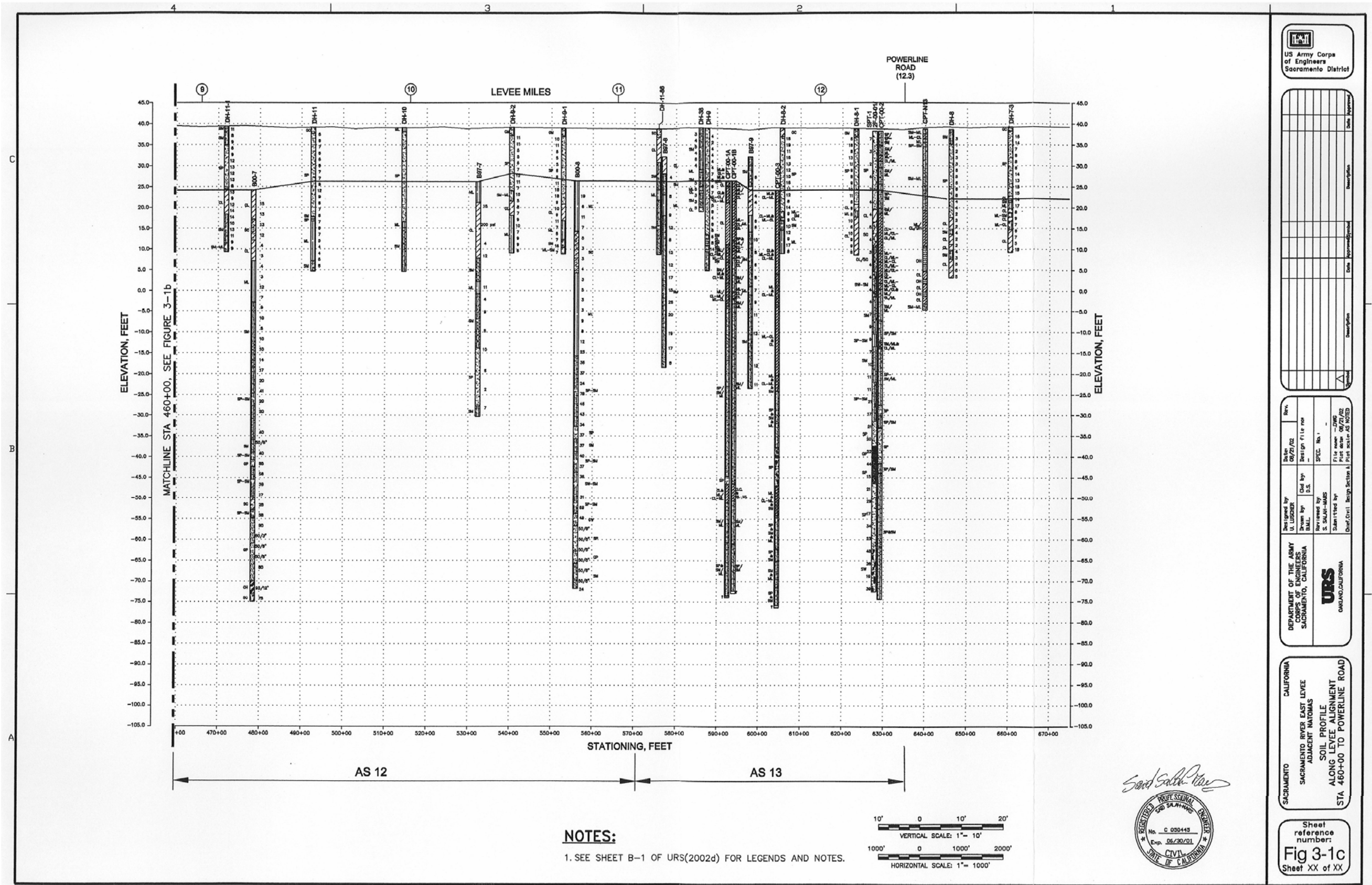


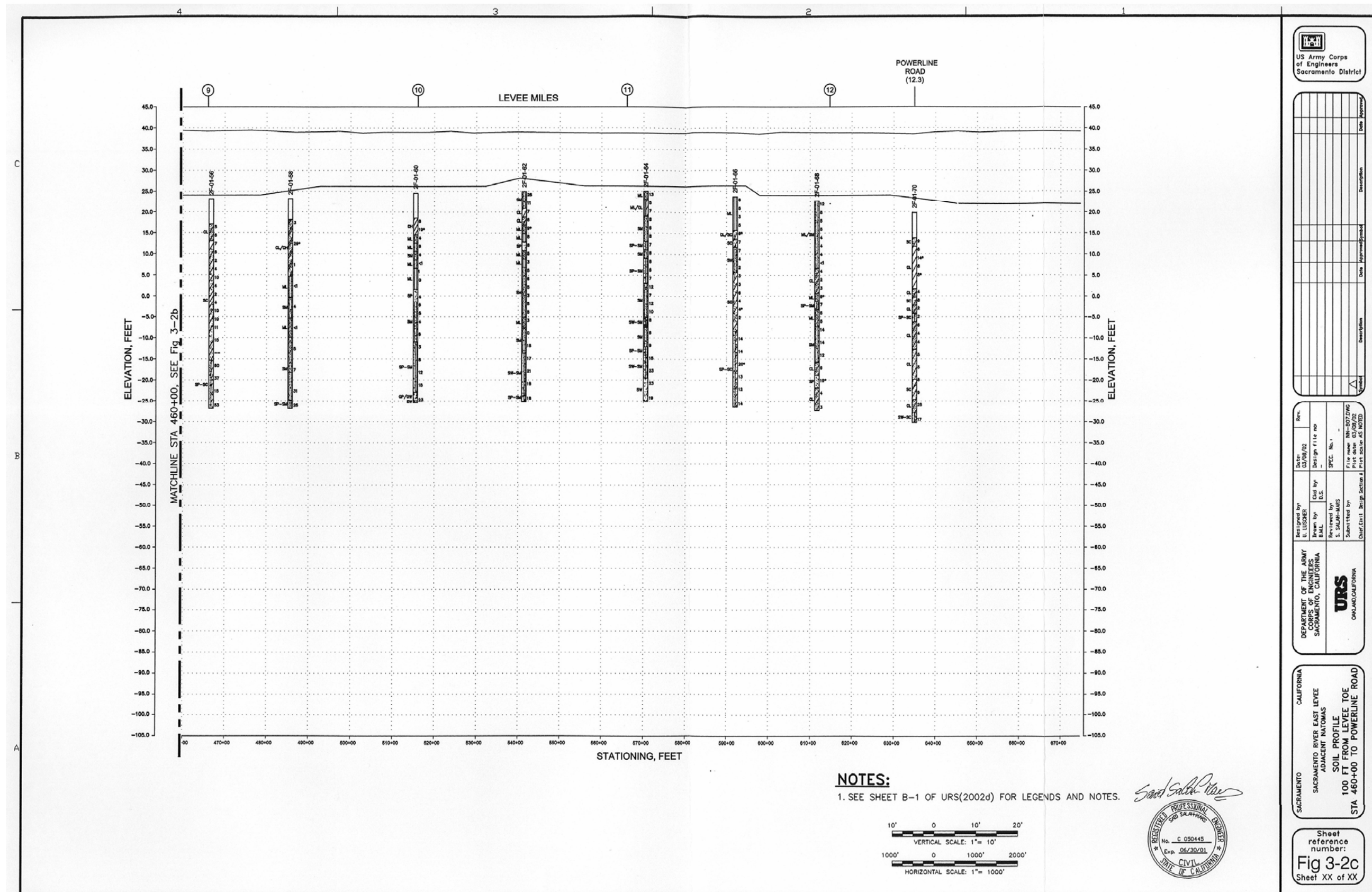






## **Appendix F: Soil Profiles, Site 3**





REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) July 2007		2. REPORT TYPE Final report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE  Geophysical Surveys for Assessing Levee Foundation Conditions, Sacramento River Levees, Sacramento, CA				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)  José L. Llopis, Eric W. Smith, and Ryan E. North				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  U.S. Army Engineer Research and Development Center Geotechnical and Structures Laboratory 3909 Halls Ferry Road Vicksburg, MS 39180-6199				8. PERFORMING ORGANIZATION REPORT NUMBER  ERDC/GSL TR-07-21	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)  Headquarters, U.S. Army Corps of Engineers Washington, DC 20314-1000				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT  Effective flood and coastal storm emergency response depends on the ability of emergency managers to obtain information on the condition of flood damage reduction structures in near-real time. This report describes the results of a series of geophysical investigations performed to determine the potential of geophysical methods to provide supplemental geologic data between existing borings in a rapid fashion in an area of complex geology located along the toe of the Sacramento River levees. The geophysical study was conducted along selected portions of the Sacramento River levee between Natomas Cross Canal and Powerline Road. Electromagnetic, ground penetrating radar, and capacitively-coupled resistivity surveys were conducted to infer soil type.					
15. SUBJECT TERMS Electrical resistivity Electromagnetic induction		Geophysics Ground penetrating radar Levee assessment		Sacramento River Sacramento River levees	
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES  69	19a. NAME OF RESPONSIBLE PERSON
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code)